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Laboratory Study of Friction in TFE Sliding Surfaces for Bridge Bearings

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Abstract:	The state-of-the-art of TFE slide surfaces in bridge bearings is summarized and the more significant parameters, which influence the coefficient of friction of TFE, are identified. A test program to investigate the influence of four of these parameters, namely, contact pressure, temperature, sliding speed and roughness of the stainless steel surface, is described. Test data are presented and analyzed. Both the static and dynamic coefficients of friction were found to increase with an increase in sliding speed and roughness of the stainless steel surface, and with a decrease in contact pressure and temperature. It is concluded that the values of the coefficient of friction given in the Ontario Highway Bridge Code follow the proper trend and are conservative, except at low temperature and high sliding speeds with a rough stainless steel surface. The initial coefficient of friction was found to be as high a five times that after fifty cycles of movement. Further needs are identified.
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LIST OF NOTATION

n	parameter used in Eqn.(1)
P	average pressure at the sliding surface
Q	parameter used in Eqn.(1)
R	surface roughness
T	temperature
V	sliding velocity
μ	coefficient of friction

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1. INTRODUCTION

Bearings utilizing tetrafluorethylene (TFE) to provide sliding surfaces are widely used in bridge structures. The merits of TFE as a material for a sliding surface in a bridge bearing are its low friction property, its chemical inertness under normal conditions, as well as its resistance to water absorption and weathering. TFE is incorporated in pot, spherical, disc and slider bearings. The low friction TFE surface is used to provide either rotation by sliding over a spherical surface, or translation by sliding on a plane surface, or a combination of both. Stainless steel is commonly used for the surface mating with the TFE.

The Ontario Highway Bridge Design Code (OHBDC) [1] specifies design requirements for TFE sliding surfaces in bridge bearings. These requirements are based largely on current practices in Ontario [2] and Europe. Only limited data are available on the performance of TFE sliding surfaces in bearings constructed from North American materials and under service conditions experienced in Ontario. Consequently, the Ministry of Transportation of Ontario (MTO) has undertaken a research program to examine the state-of-the-art and to refine the provisions in the OHBDC in relation to TFE sliding surfaces in bridge bearings in Ontario.

This report summarizes the laboratory testing carried out at Queen's University on a research project entitled "TFE Sliding Surfaces in Bridge Bearings" sponsored by MTO. Earlier work dealt with the state-of-the-art of TFE slide surfaces under Tasks 1 to 4 of the project and has been reported previously by Campbell and Kong [3].

The work described in this report relates to the following tasks:

Task 5. Conduct laboratory testing to supplement the literature study [3].

Task 6. Formulate recommendations for design requirements.

Task 7. Prepare final report.

This report represents completion of Task 7. Chapter 2 summarizes the state-of-the-art report [3], while the laboratory test program is described in Chapter 3. Test results are presented and discussed in Chapter 4. Design recommendations and further research needs are outlined in Chapter 5. Conclusions are drawn in Chapter 6. Appendix A contains data from all sixty tests in the laboratory test program.

2. STATE-OF-THE-ART OF TFE SLIDE SURFACES

The coefficient of friction is the prime parameter in the design of TFE sliding bearings for bridges since it dictates the magnitude of the forces transmitted from the superstructure to the substructure and affects the articulation of the structure.

Two coefficients of sliding friction, namely static and dynamic, exist for TFE sliding on a metallic surface. The static coefficient (μ_S) relates to the force required to start movement and the dynamic coefficient (μ_D) relates to the force to maintain movement. The static coefficient is higher than the dynamic coefficient. The higher value of the static coefficient of friction results from the phenomenon of "stick-slip", which is characterized by a short period of slowly increasing frictional force followed by a rapid fall in the force with movement.

The state-of-the-art report by Campbell and Kong [3] identified 14 parameters which affect the coefficient of friction of TFE sliding on a metallic plate. These parameters are:

dimpling and lubrication;

contact pressure;

speed of travel;

eccentric loading;

temperature;

creep;

roughness of the mating surface;

type of TFE;

attachment of the TFE to the backing plate;

surface contamination;

length of the travel path;

load and travel history;

specimen size;

wear.

The influences of these various parameters, which have been discussed in detail in [3], are summarized here.

Both dimpling and lubrication have beneficial effects on the coefficient of friction. Lubrication reduces the coefficient of friction significantly from that of a comparable unlubricated surface and the provision of dimples extends the effective life of the lubricant. The dimples serve as a reservoir for storage of the lubricant which is under hydrostatic pressure and is extruded to the sliding surface under pressure. A typical configuration of the dimples is shown in Fig. 1. Only dimpled, unfilled TFE resin with a silicone grease lubricant is permitted for use in sliding bearings for bridges in the Province of Ontario [1].

The coefficient of friction decreases with increasing contact pressure in the TFE-metallic plate interface and approaches a minimum value at a certain pressure. The magnitude of this pressure has been reported to vary between 10 MPa and 50 MPa and may be lower for a lubricated surface than for an unlubricated surface. Further, the difference between the static and dynamic coefficients of friction diminishes with increasing pressure level. The trend in reduction of the coefficient of friction with increasing pressure appears to reflect the change from elastic to plastic behavior in the TFE.

The coefficient of friction of TFE increases with sliding speed up to a speed of about 1000 mm/s and then levels off. Little information is available on sliding speeds experienced by bridge bearings in service. Thermal movements produce negligible sliding speeds compared to those induced by traffic on a bridge. Field measurements have shown maximum sliding speeds due to traffic loads at bearings as high as 70 mm/s, and speeds up to 380 mm/s may be experienced under earthquake conditions. These values are well below the speed of 1000 mm/s at which the coefficient of friction becomes independent of speed.

Accommodation of the rotation of the superstructure in a bridge relative to the substructure may result in eccentric loading patterns within the components of a bearing. Eccentricity produces moment which induces additional edge pressure on the TFE. Reduction of the pressure on an edge may cause uplift resulting in the TFE being squeezed out, while increased pressure may cause flattening of the TFE and closure of the grease dimples, resulting in impaired performance and reduction in the life of the bearing. Test data relating specifically to the effect of eccentric loading on the coefficient of friction of TFE do not appear to be available.

The coefficient of friction increases with decreasing temperature, the rate of increase becoming larger at temperatures below -20 °C. The rate of increase in the coefficient of friction with decrease in temperature is significantly lower for a lubricated surface than for an unlubricated surface. Conditions at the TFE-metallic surface interface in a bearing may be modified significantly by condensation and icing occurring at low temperature.

TFE is a visco-elastic material and exhibits creep under sustained pressure in excess of 7 MPa. Confinement of the TFE significantly reduces both the magnitude of the deformation and the time period to reach steady state conditions under a given contact pressure. TFE sheet confined in a sharp-edged recess is used in bridge bearings and the maximum sustained compressive pressure is limited to about 35 MPa. In this case, the maximum deformation, which will be in the order of one-sixth of the unconfined thickness of the TFE layer, will not affect bearing performance.

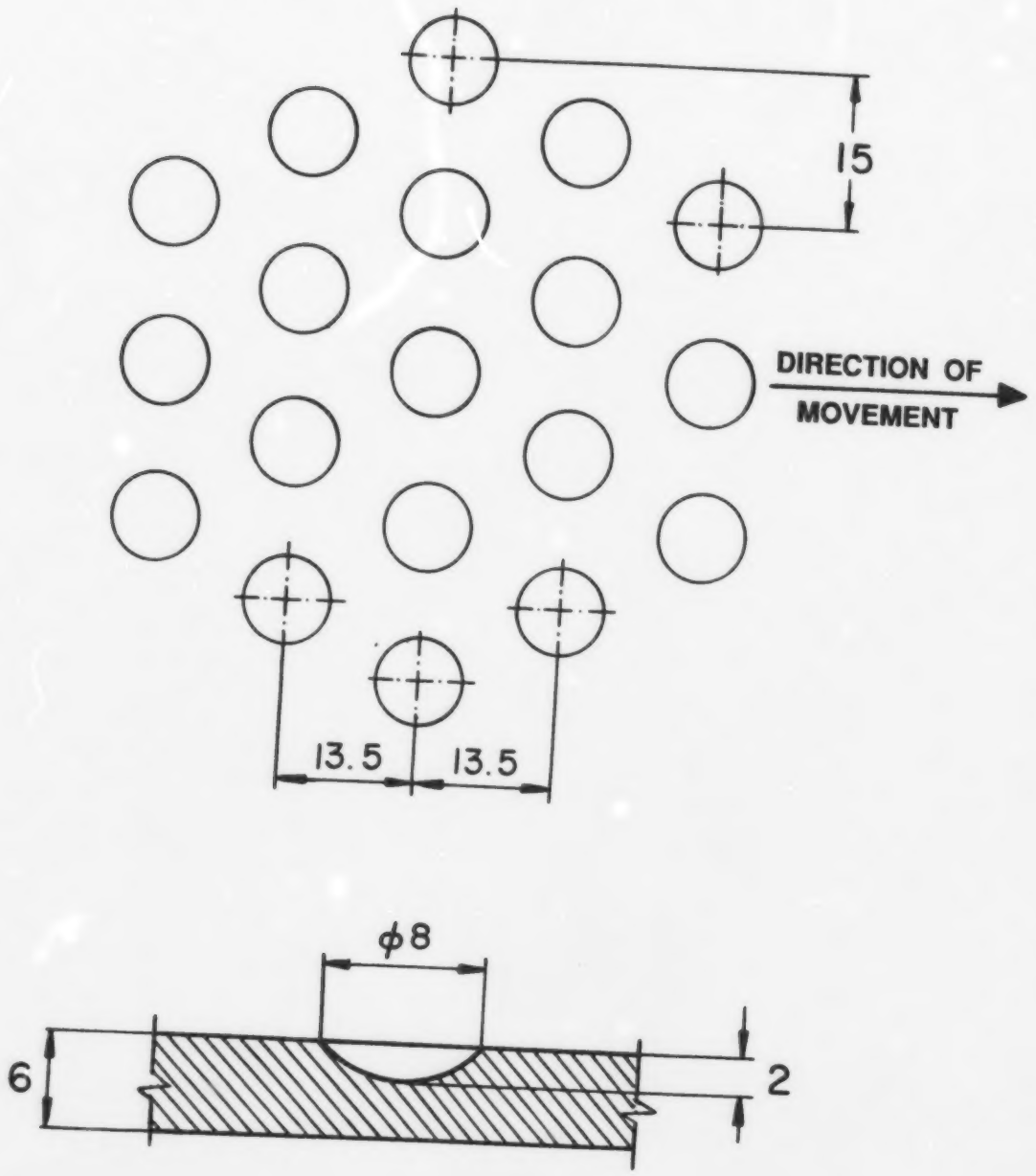


FIG.1 DIMENSIONS AND ARRANGEMENT OF GREASE DIMPLES

The mating surface in contact with the TFE is usually stainless steel. Initially, for unlubricated surfaces, the coefficient of friction for a highly polished surface is lower than that for a less polished surface, but, after a certain length of travel path, increases to approach that for a less polished surface. This trend is probably due to the phenomenon of TFE transfer to the mating surface resulting in the TFE virtually sliding on its own thin-layered deposits. On the other hand, tests have indicated that a dimpled sliding surface with lubrication shows only a few traces of wear or local TFE transfer. Therefore, whether the trend that, after an initial running-in period, the surface roughness of the mating plate does not have a significant effect on the coefficient of friction is true also for a lubricated mating surface remains unclear. The surface roughness of the TFE does not appear to have a significant effect on the friction, presumably due to the surface being soft enough to conform to the mating surface by deforming.

Virgin (unfilled) TFE resin is widely used to provide the vertical load-carrying sliding surface in a bearing, while filled TFE is commonly used on the guidebars providing lateral restraint. Virgin TFE resin has a lower coefficient of friction than filled TFE. The addition of fillers to TFE improves its resistance to wear and creep.

Ontario specifications for bridge bearings require the TFE element to be fully bonded and recessed in a rigid backing material. Bonding is intended to ensure that the TFE element will not be displaced from the recess during the life of the bearing. Elsewhere, it is common practice only to recess the TFE in the backing plate.

Virgin TFE is comparatively soft and is capable of absorbing light contamination without any apparent effect on the coefficient of friction and bearing life. However, heavy contamination with materials such as dry cement dust or sand particles substantially increases the coefficient of friction, especially during the initial period of movement. An increase in the friction coefficient of approximately 10 times has been reported when the lubricant was contaminated with dry cement dust, while complete seizure occurred in tests using an unlubricated surface contaminated with cement dust. Light and heavy contamination have not been defined quantitatively.

It has been reported that the coefficient of sliding friction for TFE increases with the total accumulated amount of movement, which is referred to as the travel path. The difference between the static and dynamic coefficient of friction decreases with increasing travel path. There is little information on the total length of travel path experienced by bearings in service. Traffic induced movements ranging from 145 m per year to 5000 m per year have been reported.

An increase in the coefficient of friction, especially the initial one, is observed when the load on the TFE is sustained for a few hours, prior to sliding. This increase occurs up to about 24 hours of sustained loading and then levels off. Hence the coefficient of friction is influenced by load and travel history. The preloading effect is important in lubricated surfaces to ensure uniformly squeezing out of the lubricant and is therefore related to size of contact surface. Hakenjos and Richter [4] suggest a minimum preloading period of one hour for 75 mm diameter discs. Discs having this diameter are used commonly for testing TFE in Europe and appear to be the accepted standard.

Wear of the TFE may have an influence on the operational life of a bearing and may increase the coefficient of friction to an unacceptably high level. The rate of wear is dependent on

sliding velocity and contact pressure. Lubrication may be expected to reduce wear, as will the addition of fillers. However, the addition of fillers tends to increase friction.

In conclusion it may be stated that the coefficient of friction at the TFE-metallic interface is the prime parameter for consideration in the design of a TFE sliding bridge bearing. The coefficient of friction is influenced significantly by lubrication, contact pressure, temperature, speed of travel and length of the travel path, as well as to a lesser degree by roughness of the metallic surface, type of TFE, surface contamination, and load and travel history. Effects of some of the parameters are not clearly documented in the literature and contradictory statements exist as to the effects of some of the parameters on the frictional properties, particularly for lubricated surfaces. These parameters are pressure, temperature, speed of travel, surface contamination, load and travel history, and roughness of the metallic surface. A study of the influences of a number of these parameters is described in this report.

3. LABORATORY TEST PROGRAM

3.1 INTRODUCTION

The existence of a relationship between the coefficient of friction of TFE and a number of the parameters identified in Chapter 2 as influencing the coefficient of friction has been suggested [3]. Validation of such a relationship would facilitate specification of the coefficient of friction for TFE sliding bearings in bridge design codes. A laboratory testing program aimed at studying the validity of this relationship is outlined in this Chapter.

3.2 SUGGESTED EXPRESSION FOR COEFFICIENT OF FRICTION

The suggested expression for the coefficient of friction, μ, of TFE is

$$\mu = QP^{n-1} \tag{1}$$

where Q and n are parameters and P is the contact pressure on the TFE. It has been suggested [5,6] that Q is primarily a function of temperature and sliding speed, while n is mainly a function of filler content of the TFE, surface lubrication, surface finish of the metallic sliding plate and loading history.

Equation (1) can be expressed in the form

$$\log \mu = \log Q + (n - 1) \log P \tag{2}$$

which indicates a linear relationship between μ and P on a logarithmic scale. Values of Q and n can be determined readily from Eqn.(2).

Tentative verification of Eqn.(2) is indicated in Figs.2 and 3 where existing test data [5,7] are plotted on logarithmic scales. Figure 2 shows that changing the interface temperature, while maintaining other parameters constant, results primarily in a change of Q only. Figure 3 indicates that the introduction of lubrication and/or variation in the surface finish of the metallic sliding plate influence both Q and n, implying that Q may be a function of surface lubrication and surface finish of the metallic sliding plate, as well as of temperature.

In order to define the coefficient of friction adequately, data should be generated from tests so that the parameters Q and n contained in Eqn.(1) can be evaluated under various working conditions. The Ontario Specification for Bearings [8] stipulates that only dimpled unfilled TFE resin with a silicone grease lubricant conforming to US Military Specification MIL-S-8660C [9]

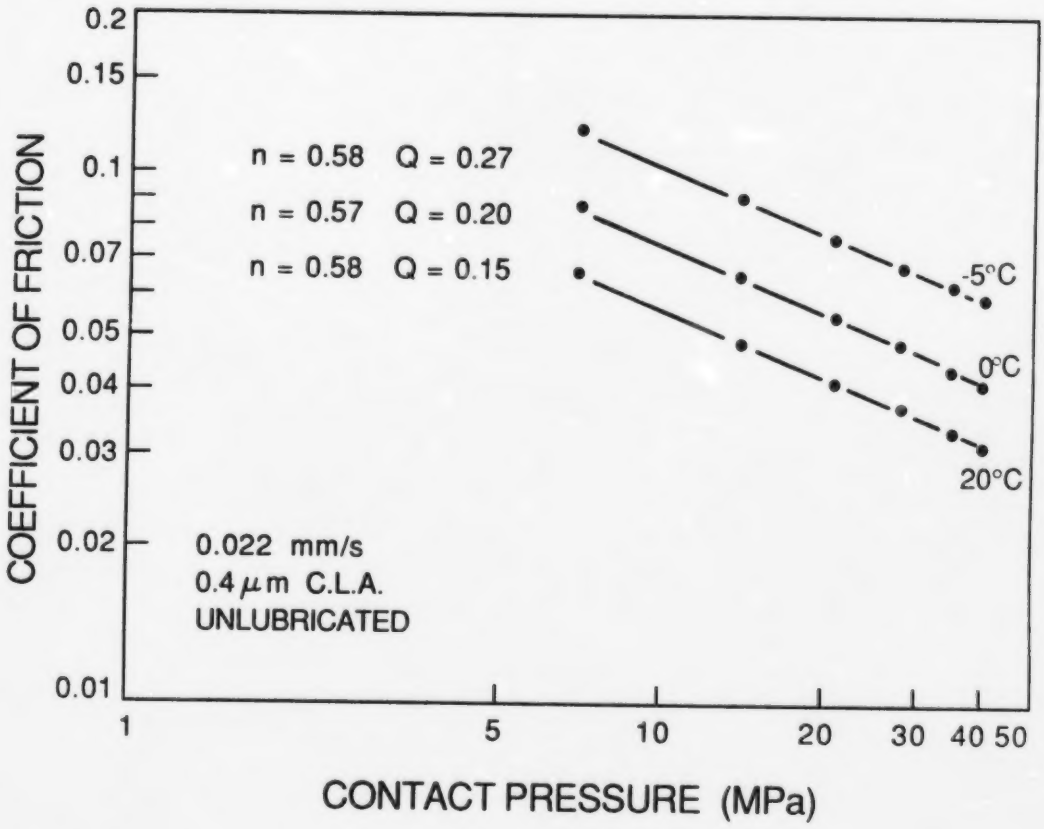


FIG.2 EFFECT OF TEMPERATURE ON THE COEFFICIENT OF FRICTION [5]

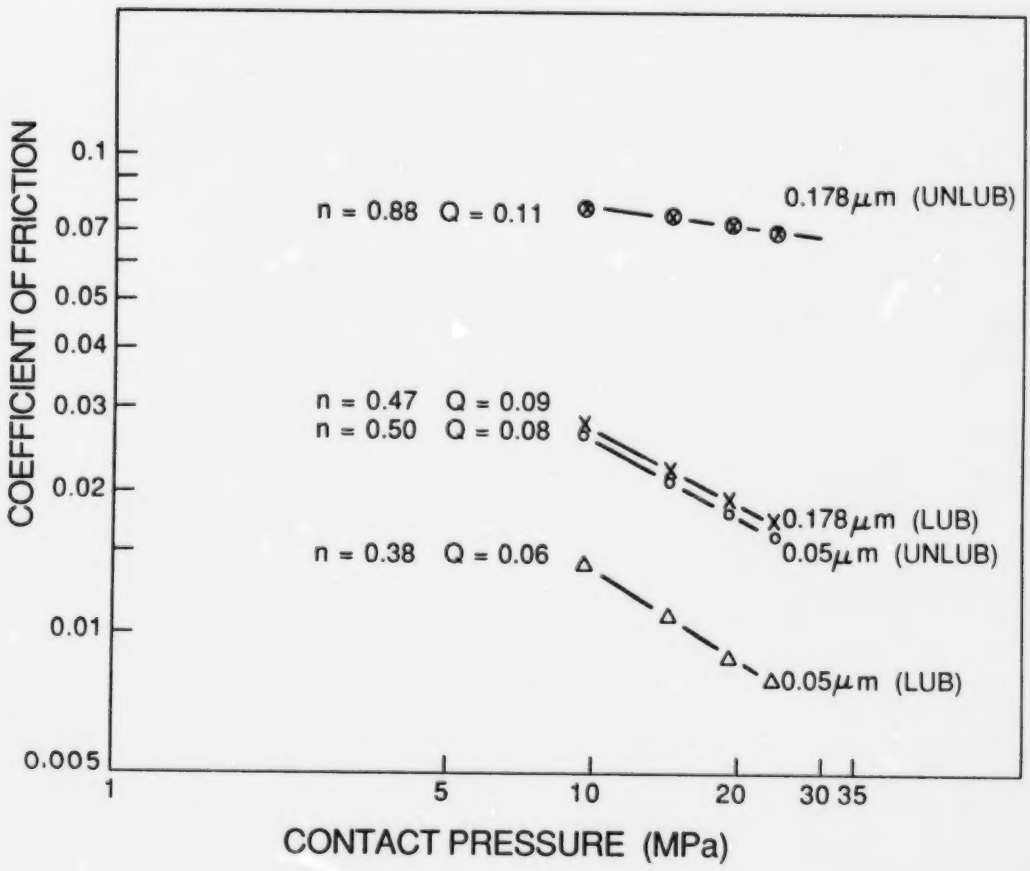


FIG.3 EFFECT OF SURFACE FINISH AND LUBRICATION ON THE COEFFICIENT OF FRICTION [7]

should be used in sliding bearings for bridges. Consequently, for this study, the parameters which will affect the frictional properties of a TFE sliding surface and which need to be investigated by testing have been limited to: contact pressure, temperature, speed of travel, and roughness of the metallic sliding plate. Loading history was kept uniform throughout the test program.

3.3 TEST PROGRAM

The ranges of above parameters considered for the test program are given in Table 1.

TABLE 1 RANGES OF PARAMETERS

Parameter	Range
Pressure, P (MPa)	10, 15, 25, 30, 45
Temperature, T (°C)	-25, 20
Speed of travel, V (mm/s)	0.08, 1, 20
Roughness of metallic plate, R (μm)	0.03, 0.34

These ranges reflect the conditions to which TFE sliding bearings may be subjected in practice and also limitations of the available test equipment. Maximum pressures of 30 MPa and 45 MPa are specified [1] for TFE sliding surfaces in bridge bearings under dead and total load, respectively. A temperature of -25 °C represents the lowest temperature attainable in the cold room facility at Queen's University. The range of speed of travel covers that from the relatively slow temperature induced movement to the expected relatively fast speed during passage of traffic on a bridge structure and are within the capabilities of the testing rig. A 0.25 μm (arithmetic average) finish is required for a plane surface according to the Ontario Specification for Bearings [8]. The two selected roughnesses correspond to commercially available No.8 and No.4 finishes [10], respectively, and lie on either side of the 0.25 μm value. A roughness of 0.03 μm was measured for a No.8 finish surface, while 0.34 μm was measured for a No.4 finish using a Surtronic Surface Roughness Tester. Both measurements were made perpendicular to the direction of polishing. A No.8 finish is normally used for the stainless steel in bridge bearings in Ontario.

The ranges of parameters given in Table 1 are covered in the twelve series of tests outlined in Table 2. In each series, five individual specimens of TFE were tested under contact pressures of 10, 15, 25, 30 and 45 MPa, respectively, while temperature, surface roughness and travel speed were maintained as indicated. The pressure was computed using the gross area of the TFE surface.

TABLE 2 DETAILS OF TEST SERIES

Series	Temperature (°C)	Surface Roughness (μm)	Travel Speed (mm/s)
1	20	0.03	0.08
2	20	0.03	1.0
3	20	0.03	20.0
4	20	0.34	0.08
5	20	0.34	1.0
6	20	0.34	20.0
7	-25	0.03	0.08
8	-25	0.03	1.0
9	-25	0.03	20.0
10	-25	0.34	0.08
11	-25	0.34	1.0
12	-25	0.34	20.0

The following conditions applied in all tests:

a) A single TFE specimen was subjected to minimum of 50 cycles, using a stroke of ±10 mm/cycle to give a travel path of 40 mm per cycle.

b) The specimens of dimpled, lubricated TFE resin had a diameter of 75 mm and a thickness of 4.5 mm and were recessed to a depth of 2.5 mm in a steel backing plate.

c) Commercially available stainless steels having a thickness of 1.5 mm and surface roughnesses as specified were used.

d) A dwell of load period of 12 hours prior to testing was used.

e) New specimens of TFE and stainless steel were used.

Fifty cycles were selected in order to limit the slow speed (0.08 mm/s) tests to a reasonable time period. Three hundred cycles were usually completed in the intermediate speed (1.0 mm/s) tests and a minimum of 8000 cycles was completed in the fast speed (20 mm/s) tests. A stroke of ±10 mm was chosen arbitrarily from values used in previous studies on friction of TFE. Test specimens of TFE having a diameter of 75 mm appear to be the accepted standard in Europe. The minimum thickness and free height of TFE specimen are stipulated in the Ontario Specification for Bearings [8]. AASHTO [11] specifies a dwell period of 12 hours when carrying out a friction test on TFE.

The five tests in each series were designated by a double numbering system. The first number refers to the particular series and the second number refers to the pressure of 10, 15, 25, 30 or 45 MPa, respectively. For example, Test 3-30 was the test in Series 3 at 30 MPa pressure and having a temperature of 20 °C, a surface roughness of the stainless steel of 0.03 μm and a travel speed of 20 mm/s (see Table 2).

3.4 TEST SET-UP

The self-straining rig used for the testing program is shown in Figs.4 and 5. This rig is capable of subjecting a TFE-stainless steel interface to cyclic sliding movement at different speeds under different levels of contact pressure. A rigid base beam provides support for both the vertical and horizontal loading systems.

A 75 mm diameter, 4.5 mm thick dimpled TFE specimen, recessed to a depth of 2.5 mm in a 25 mm thick mild steel plate, is compressed against a stainless steel sliding plate by means of a vertical hydraulic ram acting through a spherical bearing to ensure concentric loading. The 1.5 mm thick stainless steel plate having dimensions 280 mm by 240 mm is attached to a 25 mm thick mild steel backing plate by means of clamping screws around its perimeter. This backing plate is attached to a sliding platform which moves horizontally on steel rollers. The surfaces of the backing plates for the TFE and the stainless steel were machined in order to ensure flat surfaces. Two 25 mm thick precision-ground flat steel plates, one attached to the top surface of the base beam and the other to the bottom surface of the sliding platform, formed the contact surfaces for the rollers, which were made from high strength, distortion free, 100 mm diameter precision ground steel shafting.

Horizontal movement is transmitted to the sliding platform by means of a hydraulic actuator incorporated in a MTS closed-loop testing system. The line of action of the horizontal load is through the TFE-stainless steel interface. The top surface of the backing plate for the stainless steel plate was aligned with the surface of the ground plate on the bottom of the sliding platform to ensure motion in the line of the horizontal actuator. The sliding speed and stroke of horizontal movement are controlled by the MTS system. A triangular displacement-time function was used to provide a uniform speed of travel over the stoke. Horizontal movement of the sliding platform was monitored by a displacement transducer.

Load cells were used to measure the vertical and horizontal load levels. Two load cells were used to measure horizontal load, one for the load provided to the moving platform by the hydraulic actuator and the other for the load actually transmitted to the TFE specimen. The latter load cell was mounted on a horizontal reaction beam and attached to the TFE backing plate by a linkage component (see Fig.5(c)). The difference in load levels from these two load cells gave a measure of the frictional resistance of the rollers. The coefficient of friction at the TFE-stainless steel interface is determined from the ratio of the horizontal to vertical load.

The temperature of the TFE-stainless steel interface was monitored by a temperature transducer embedded in the backing plate for the stainless steel. The temperature and the humidity of the environment of the rig were also monitored. The tests at -25 °C were conducted with the rig located in a cold room facility.

Springs located at the upper end (Fig.5(b)) of the vertical loading system ensured that the load level remained fairly stable during the twelve hour preloading period during which creep of the TFE took place. These springs served also as a pivot for the upper end of the vertical hydraulic ram. The lower end of the ram was restrained, in the direction of the horizontal loading, by the linkage from the horizontal reaction beam to the TFE backing plate, and at right angles by two linkages from the backing plate to the two vertical members of the test rig as shown in Fig.5(c).

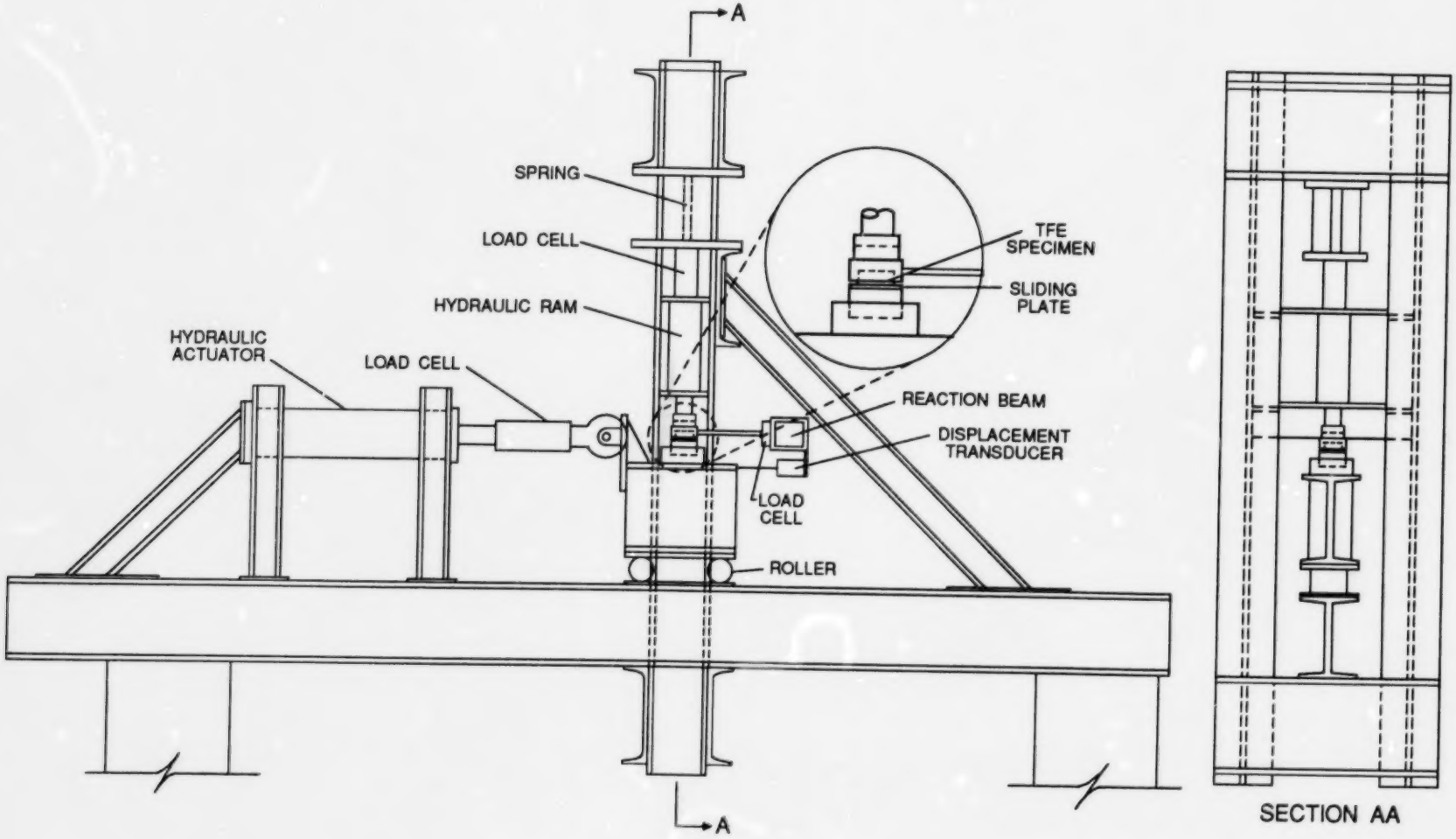
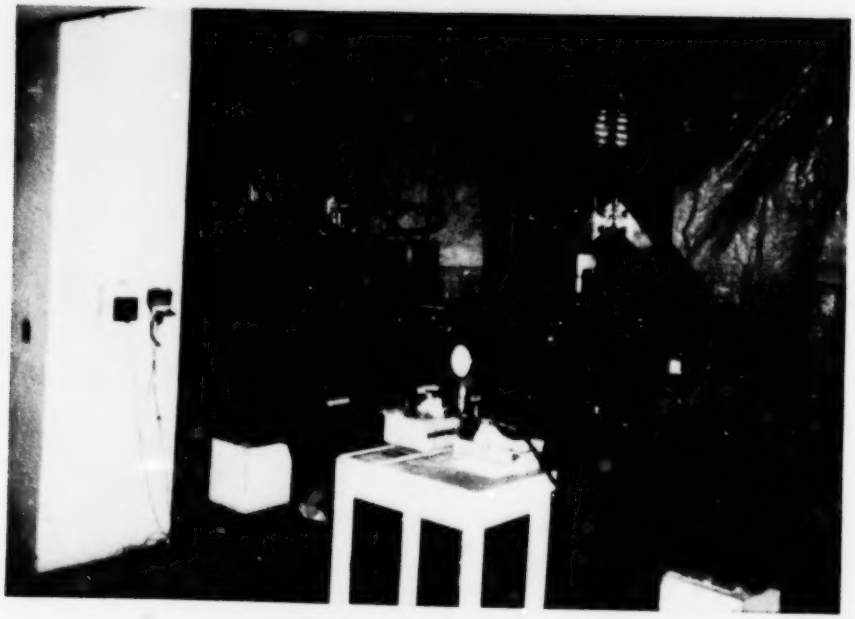
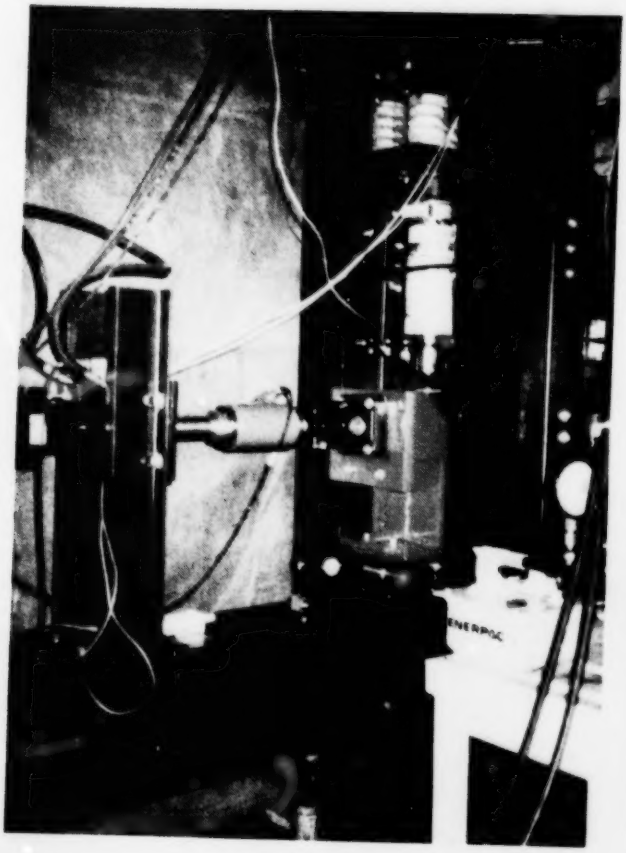


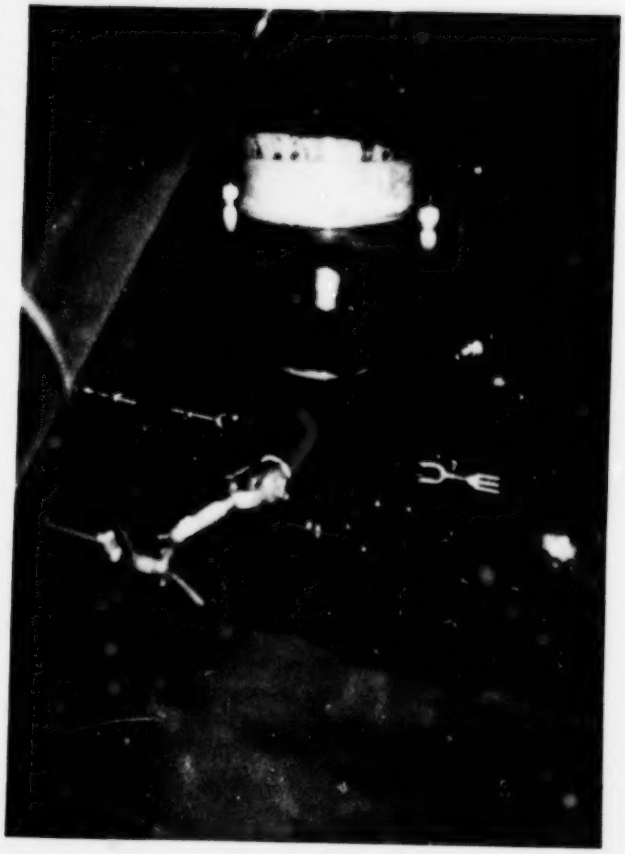
FIG.4 DIAGRAMMATIC REPRESENTATION OF TESTING RIG



(a)



(b)



(c)

FIG.5 PHOTOGRAPHS OF TESTING RIG

The TFE, stainless steel and lubricant used in the tests were obtained from the same sources as those used by a Canadian bearing manufacturer. The dimpled TFE, which was manufactured in West Germany, was obtained from Norton Chemplast, the stainless steel from Drummond-McCall and the lubricant (Molykote 44) from Wercholoz Canada Inc. Molykote 44 is a silicone oil thickened with lithium soap. Typical properties supplied by the manufacturer of Molykote 44 indicate that it comforms to the penetration, bleed and evaporation requirements given in MIL-S-8660C [9]. However, the bottom of the temperature range is given as -40 °C compared with -48 °C in MIL-S-8660C.

The 75 mm diameter TFE discs were machined from dimpled TFE sheet ensuring that the disc was centred on a dimple. This resulted in a concentric arrangement of dimples on the disc. The diameter of the disc was such that it was a snug fit for the recess in the steel backing plate. Lubricant was applied to the dimpled surface of the TFE using a paint scraper and care was taken to ensure that all the dimples were filled with lubricant. The rectangular specimens of stainless steel were cut from a sheet having the required finish and were mounted on the sliding platform so that the direction of movement was perpendicular to the direction in which the stainless steel was polished. The surface roughness of the sheet is higher perpendicular to the direction of polishing. Prior to testing, the surface of the stainless steel plate was cleaned using acetone.

The backing plate containing the TFE specimen was placed on the stainless steel plate in the test rig with the TFE specimen aligned so that the direction of the movement of the TFE relative to the stainless steel was as indicated in Fig. 1. This ensured that the lubricant was smeared over the entire region of movement of the TFE. The desired level of vertical load was applied for a period of twelve hours with the specimen located at the midstroke position. Subsequently the specimen was subjected to the required number of cycles of movement. The test rig performed satisfactorily at both 20 °C and -25 °C.

All data were recorded and stored on floppy discs by a MTS data acquisition system capable of sampling at a rate of 1000 data points per second. A trace of the horizontal force-displacement relationship could be viewed on a screen and a hard copy of the trace could also be obtained. A typical trace for a complete cycle is shown in Fig.6. A total of 126 data points per cycle was recorded for the trace in the slow and intermediate speed tests. This number was reduced to 64 in the high speed tests.

During application of the vertical load to the TFE specimen, some preloading of the horizontal linkage from the TFE backing plate to the load cell invariably occurred. As a result, as can be seen in Fig.6, the force-displacement trace was related to an apparent rather than an actual datum. The amount of preloading was determined from the average of the peak values of the horizontal to vertical force ratio at each end of the stroke and the actual datum was established as indicated in Fig.6. This process was repeated for a number of cycles in each test in order to establish a realistic value of the preload. The maximum value of the horizontal to vertical force ratio (related to the actual datum) was taken as the static coefficient of friction in the cycle, while the minimum value was taken as the dynamic coefficient of friction. The peak values of the force ratio occur at each end of the stroke where the direction of movement is reversed.

Data obtained from the sixty tests are given in Appendix A in the form of plots of coefficient of friction (C.O.F.) versus number of cycles. Both static and dynamic values of the coefficient of friction are given. One, two or three plots are presented for each test depending on the

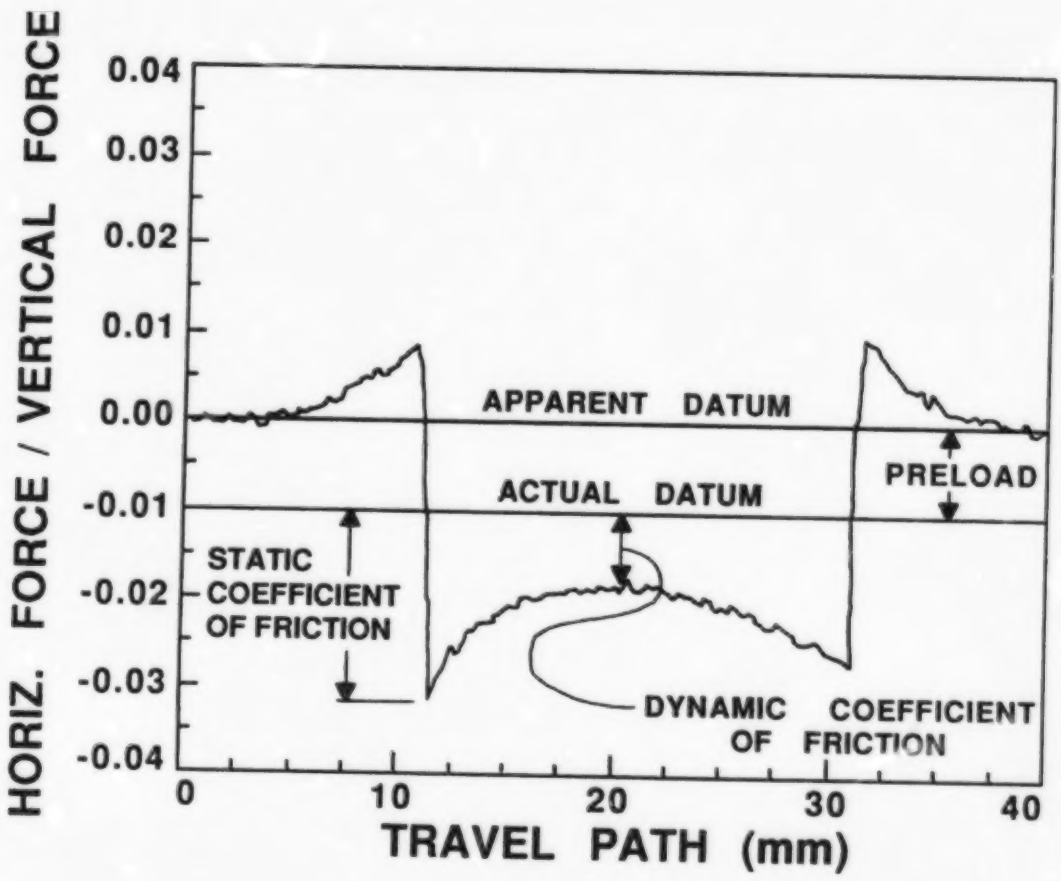


FIG.6 VARIATION OF THE RATIO OF HORIZONTAL TO VERTICAL FORCE OVER A CYCLE

number of cycles of movement completed during the test. The first plot shows data from 0 to 50 cycles, the second plot shows that from 50 up to as high as 8000 cycles, while the third plot shows data beyond 8000 cycles. In a few tests data from the first cycle of movement were lost due to malfunctioning of the data acquisition system.

Values of the initial coefficient of friction, together with those at 50 cycles and at a specified larger number of cycles, were extracted from the test data and are presented in Tables 3 and 4. In addition, various ratios of these coefficients of friction are given in Tables 3 and 4. The initial coefficient of friction is that at the start of movement from midstroke in the first cycle.

TABLE 3 COEFFICIENTS OF FRICTION AFTER VARIOUS CYCLES AT 20 °C

TEST NO.	COEFFICIENT OF FRICTION							RATIOS		
	INITIAL		AT 50 CYCLES		AT SPECIFIED CYCLES					
	STATIC (1)	DYNAMIC	STATIC (2)	DYNAMIC (3)	STATIC (4)	DYNAMIC	CYCLES	(1)/(2)	(4)/(2)	(3)/(2)
1-10	.0116	.0087	.0108	.0080						
1-15	.0135	.0820	.0072	.0051				1.07		.74
1-25	.0058	.0046	.0038	.0028				1.88		.71
1-30	.0055	.0037	.0038	.0027				1.53		.74
1-45			.0031	.0021	.0033	.0025	106	1.45	1.06	.71 .68
2-10	.0136	.0068	.0077	.0050	.0100	.0060	375	1.77	1.30	.65
2-15	.0140	.0092	.0052	.0032				2.69		.62
2-25			.0040	.0026						.65
2-30			.0040	.0018						.45
2-45	.0086	.0079	.0033	.0011				2.61		.33
3-10	.0334	.0172	.0126	.0064	.0198	.0112	8000	2.65	1.57	.51
3-15	.0473	.0258	.0081	.0028	.0127	.0041	8000	5.84	1.57	.35
3-25	.0338	.0181	.0063	.0035	.0106	.0065	8000	5.37	1.68	.56
3-30	.0290	.0175	.0066	.0044	.0120	.0078	18000	4.39	1.82	.67
3-45	.0230	.0160	.0045	.0030	.0059	.0040	5000	5.11	1.31	.67
4-10	.0149	.0100	.0169	.0112						
4-15			.0146	.0101				.88		.66
4-25	.0089	.0063	.0092	.0066						.69
4-30	.0062	.0039	.0082	.0060				.97		.72
4-45	.0054	.0054	.0062	.0047				.76		.73
5-10	.0167	.0132	.0253	.0212	.0318	.0250	400	.87		.76
5-15	.0430	.0280	.0300	.0260	.0253	.0208	360	.66	1.26	.84
5-25	.0146	.0118	.0176	.0140	.0201	.0153	400	1.43	.84	.87
5-30	.0114	.0095	.0141	.0128	.0175	.0142	360	.83	1.14	.80
5-45	.0143	.0125	.0124	.0106	.0117	.0910	305	.81	1.24	.91
6-10	.0689	.0530	.0387	.0310	.0406	.0276	8000	1.15	.94	.85
6-15	.0528	.0381	.0274	.0233	.0270	.0217	10600	1.78	1.05	.80
6-25	.0331	.0191	.0169	.0136	.0170	.0140	10600	1.93	.99	.85
6-30	.0417	.0218	.0141	.0107	.0109	.0830	10400	1.96	1.01	.80
6-45	.0328	.0185	.0104	.0078	.0077	.0610	8000	2.96	.77	.76
								3.15	.74	.75

Blanks indicate that data were not available

TABLE 4 COEFFICIENTS OF FRICTION AFTER VARIOUS CYCLES AT -25 °C

TEST NO.	COEFFICIENT OF FRICTION							RATIOS		
	INITIAL		AT 50 CYCLES		AT SPECIFIED CYCLES					
	STATIC (1)	DYNAMIC	STATIC (2)	DYNAMIC (3)	STATIC (4)	DYNAMIC	CYCLES	(1)/(2)	(4)/(2)	(3)/(2)
7-10	.0603	.0279	.0286	.0213				2.11		.74
7-15	.0232	.0140	.0172	.0118				1.35		.69
7-25	.0225	.0112	.0183	.0136				1.23		.74
7-30	.0143	.0105	.0097	.0070				1.47		.72
7-45	.0084	.0055	.0080	.0059				1.05		.74
8-10	.0549	.0251	.0220	.0168	.0341	.0233	335	2.50	1.55	.76
8-15	.0387	.0197	.0200	.0149	.0253	.0187	335	1.94	1.26	.75
8-25	.0576	.0420	.0254	.0200	.0267	.0220	200	2.27	1.05	.79
8-30	.0229	.0139	.0103	.0080	.0125	.0874	136	2.22	1.21	.78
8-45	.0537	.0340	.0178	.0155	.0225	.0193	235	3.02	1.26	.87
9-10	.1000	.0526	.0328	.0290	.0814	.0686	7400	3.05	2.48	.88
9-15	.1120	.0673	.0277	.0223	.0552	.0467	8000	4.04	1.99	.81
9-25	.0809	.0489	.0265	.0230	.0317	.0270	9546	3.05	1.20	.87
9-30	.0844	.0505	.0266	.0238	.0331	.0128	8000	3.17	1.24	.89
9-45	.0590	.0395	.0187	.0163	.0280	.0263	8000	3.16	1.50	.87
10-10	.0420	.0247	.0291	.0154				1.44		.53
10-15	.0264	.0161	.0299	.0159				.88		.53
10-25	.0158	.0102	.0156	.0078				1.01		.50
10-30	.0256	.0173	.0252	.0196				1.02		.78
10-45	.0156	.0109	.0208	.0167				.75		.80
11-10	.0660	.0528	.0648	.0488	.0613	.0476	350	1.02	.95	.75
11-15	.0486	.0259	.0372	.0276	.0461	.0336	300	1.31	1.24	.74
11-25	.0469	.0307	.0267	.0226	.0340	.0293	235	1.76	1.27	.85
11-30	.0240	.0166	.0148	.0118	.0259	.0223	358	1.62	1.75	.80
11-45	.0296	.0225	.0205	.0165	.0296	.0257	350	1.44	1.44	.80
12-10	.1480	.0770	.0500	.0434	.0573	.0434	8200	2.96	1.15	.87
12-15	.0945	.0559	.0430	.0365	.0680	.0570	8000	2.20	1.58	.85
12-25	.0928	.0515	.0432	.0370	.0468	.0382	8000	2.15	1.08	.86
12-30	.0704	.0467	.0220	.0212	.0350	.0303	8000	3.20	1.59	.96
12-45	.0796	.0595	.0247	.0209	.0240	.0209	8000	3.22	.97	.85

Blanks indicate that data were not available

4. ANALYSIS OF TEST DATA

4.1 GENERAL

Phenomena observed during the tests are discussed prior to an analysis of the data obtained from the tests, since these observations reflect on some of the trends exhibited by the test data.

4.2 OBSERVATIONS DURING TESTS

In the tests using the rough (No.4 finish) stainless steel plate, the lubricant became darker in colour and stiffer in consistency with increasing number of cycles than in the corresponding tests using the smooth (No.8 finish) stainless steel plate. This can be seen in Fig.7 which shows four TFE discs, one without grease (top left), one with grease prior to testing (top right), one after testing to 8265 cycles at 20 mm/s with the smooth plate (bottom left) and one after testing to 8225 cycles at 20 mm/s with the rough plate (bottom right). The grease from the smooth stainless steel plate test is discoloured by the presence of flakes of TFE resulting from wear of the TFE. The colour of the grease from the test using the rough stainless steel plate is very dark presumably as a result of contamination with residuals of the abrasive used in polishing the stainless steel.

Significant wear of the TFE was observed only in Test 9-45 carried out using a smooth stainless steel plate at a contact pressure of 45 MPa and a temperature of -25 °C. Wear was characterized by a deposit of flakes of TFE on the stainless steel plate at each end of the stroke, as shown in Fig.8. A loss in weight of 4% in the TFE disc was measured after 8000 cycles in this test. By comparison in the corresponding test (Test 12-45) using the rough stainless steel the loss in weight was only 0.5%. Traces of wear were observed also in Test 9-30 using the smooth stainless steel plate at a contact pressure of 30 MPa and a temperature of -25 °C. No wear was observed in any other test.

The shape of the force ratio-displacement trace for a cycle differed, particularly during the early cycles of movement, for the rough and smooth stainless steel plates. This is obvious in Fig.9 which shows traces from the second cycle of movement in Test 2-25, where smooth stainless steel plate was used (Fig.9(a)), and Test 5-25, where rough stainless steel plate was used (Fig.9(b)). Figure 9(b) shows a more pronounced difference between the ratio of the horizontal to vertical force at mid-stroke and at the end of the stroke than does Fig.9(a). After about 30 cycles, the shape of the trace for the rough plate approached that of the smooth plate.

The temperature of the TFE specimen increased with the number of cycles in the fast speed tests using both smooth and rough stainless steel plates. After 8000 cycles at 20 °C, the increase was approximately 2 °C for the smooth plate and 3 to 4 °C for the rough plate, while at -25 °C the corresponding increase was from 5 to 10 °C for both plates and increased with contact pressure.

Frost was observed outside the contact area on the stainless steel plates in the tests at -25 °C. It was not possible to determine if this also existed within the contact area and thus the influence of frost on the coefficient of friction could not be assessed.

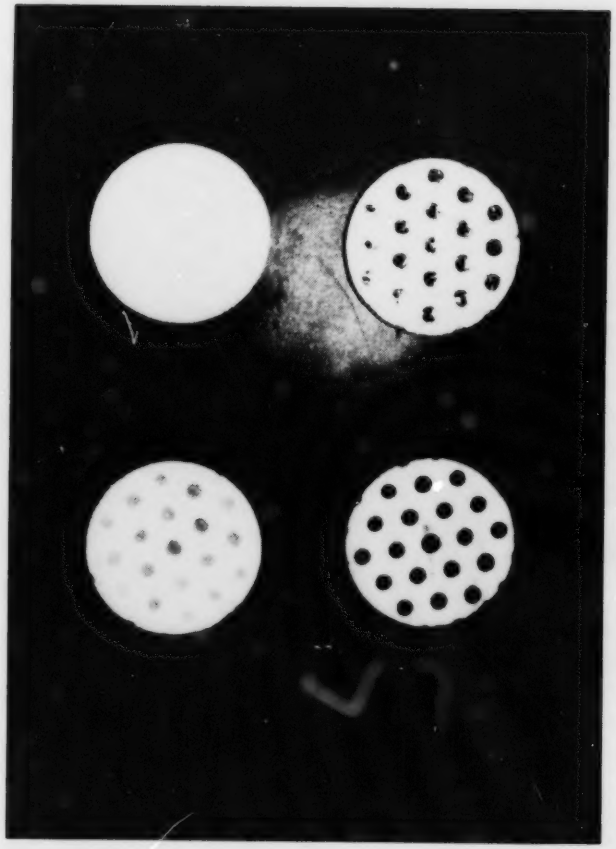


FIG.7 DISCOLORATION OF LUBRICANT ON TFE DISCS

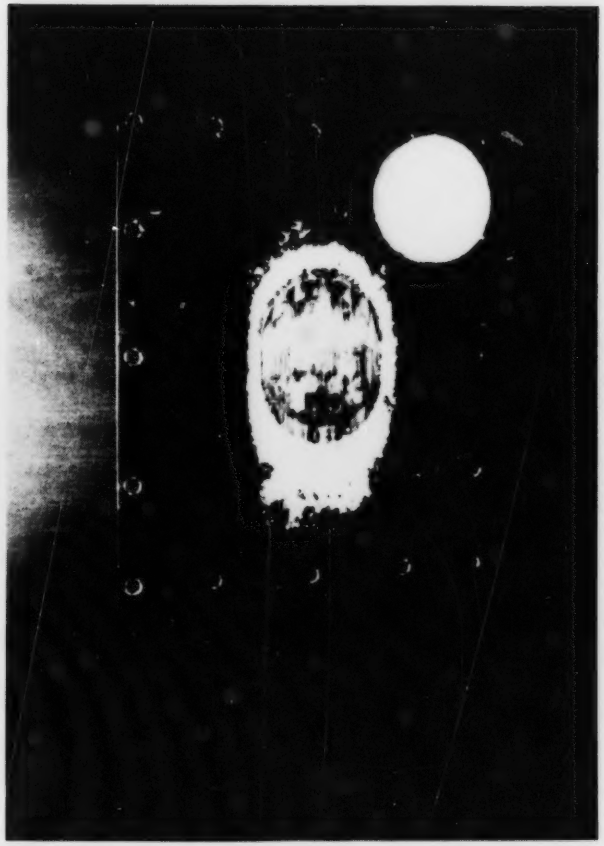


FIG.8 DEPOSIT OF TFE FLAKES INDICATING WEAR

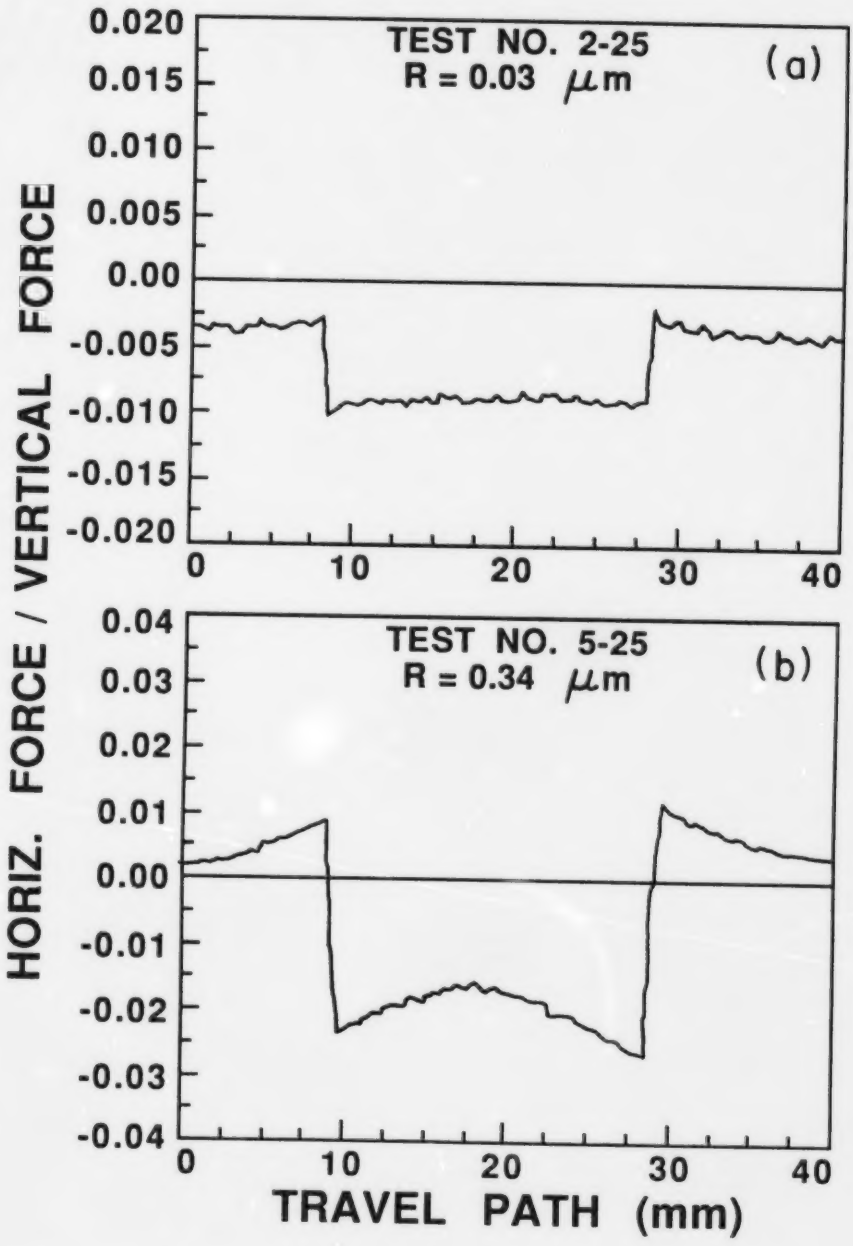


FIG.9 TRACES OF VARIATION OF HORIZONTAL TO VERTICAL FORCE RATIO FOR ROUGH AND SMOOTH STAINLESS STEEL PLATES

4.3 OBSERVATIONS FROM TEST DATA

A number of observations may be made from the test data presented in Appendix A. The test data can be subdivided into four sections according to the roughness of the stainless steel plate and the temperature, with each section containing data from the three series of tests at three different speeds with five tests in each series.

(a) Tests 1-10 to 3-45

These fifteen tests were carried out at 20 °C using No.8 finish stainless steel. In all three series, the highest value of the coefficient of friction, both static and dynamic, was recorded during the initial movement. A rapid drop in the magnitudes of both coefficients of friction occurred after 1 cycle of movement and the magnitude of the drop increased with speed of movement. A further decrease occurred up to about five cycles after which both coefficients appeared to stabilize and remain fairly constant up to 50 cycles. For each particular test, the difference between the static and dynamic coefficients of friction remained fairly constant with increasing number of cycles. Additional data, after 120 and 370 cycles for Tests 1-45 and 2-10, respectively, indicate a slight increase in both the coefficients of friction beyond 50 cycles. For Series 3 tests, data obtained beyond 50 cycles indicated an increase in both the coefficients of friction up to about 1000 cycles, after which the values stabilized and remained fairly constant up to 8000 cycles at which point the tests were discontinued, except in Test 3-30 where 18000 cycles were completed. The coefficients of friction remained constant between 8000 and 18000 cycles in this test.

(b) Tests 4-10 to 6-45

These fifteen tests were carried out at 20 °C using No.4 finish stainless steel. In Series 4 and 5, at low and intermediate speeds respectively, it was observed that the initial static coefficient of friction was lower than that in the first cycle, except in Tests 5-15 and 5-45. Subsequent to the first cycle, the static coefficient of friction decreased and stabilized after about five cycles, except in Test 5-10 where a significant increase occurred between 5 and 30 cycles. On the other hand, in all the tests of Series 4 and 5, the dynamic coefficient of friction decreased over the first cycle, increased over the next four or five cycles and then stabilized. After 5 cycles the difference between the static and dynamic coefficients remained fairly constant with increasing cycles up to 50 cycles. The trends in Series 6 tests, carried out at 20 mm/s, were similar to those described for Series 1, 2 and 3 tests. Data beyond 50 cycles up to 305 or 400 cycles for Series 5 tests indicated either a slight increase or decrease in the coefficients of friction, while very little difference was observed for the values in Series 6 tests beyond 50 cycles up to as many as 10600 cycles in three of the tests. This indicates that the observed contamination of the lubricant had little influence on the coefficient of friction. The variation in the static coefficient of friction beyond 50 cycles can be seen from the ratios in the column entitled (4)/(2) in Table 3.

(c) Tests 7-10 to 9-45

The trends during the first 50 cycles in Series 8 and 9 tests, carried out at -25 °C using No.8 stainless steel, were similar to those in the corresponding tests (Series 2 and 3) at 20 °C. In Series 7 tests, both the static and dynamic coefficients decreased over the first two cycles but then increased and stabilized after about ten cycles. Again, the difference between the static and dynamic coefficients remained fairly constant with increasing cycles up to 50 cycles. Additional data from Series 8 and 9 tests showed a slight increase in the coefficients of friction beyond 50 cycles, with the exception of Test 9-10 where the increase was about 2.5 times between 50 and 1500 cycles,

subsequent to which it remained fairly constant. It appears that the significant wear of the TFE observed in Test 9-45 did not have a significant influence on its coefficient of friction.

(d) Tests 10-10 to 12-45

The trends in Series 10 tests, carried out at -25 °C using No.4 stainless steel, were an increase in the static coefficient of friction over the first five cycles followed by relatively stable values up to 50 cycles. The trends in Series 11 tests were different from those in the corresponding Series 5 tests at 20 °C and in fact were similar to those in Series 6 tests. The trends in Series 12 tests were also similar to those in the corresponding Series 6 tests. An increase in the values of the coefficients of friction after 50 cycles was observed for Series 11 tests (see Table 4), while in Series 12 tests, the values increased between 50 and 1000 cycles and then remained fairly constant up to 8000 cycles.

The above observations indicate that, with the exception of the tests in Series 4,5,7 and 10, the coefficient of friction is a maximum at first movement and decreases progressively over the first five cycles of movement. Deviation from this trend in Series 4 and 5 tests may be due to how effectively the lubricant is spread during the initial movement of the TFE on the rough stainless steel plate. In these tests the lower value of the static coefficient of friction occurred at mid-stroke where the lubricant had been present under pressure for the twelve hours preloading period, whereas the peak coefficient of friction occurred during the first cycle at the end of the stroke where part of the surface of the stainless steel plate was receiving lubricant for the first time. The absence of this deviation in Series 6 tests would suggest that, for the rough plate, the influence of the lubricant on the coefficient of friction may not be as significant during the initial cycles at higher speeds. The trends in Series 7 and 10 tests are similar to those in Series 4 and 5 tests. The appearance of this trend in Series 7, where the smooth stainless steel plate is used, indicates that the spread of the lubricant may be hindered by the lower temperature of this test. The lack of this trend in Series 11 tests would suggest that the influence of the lubricant on the coefficient of friction is less pronounced at low temperature. The behaviours in the low temperature tests may also be influenced by icing at the TFE-stainless steel interface.

4.4 ANALYSIS OF TEST DATA

Based on the above observations it may be concluded that, with the exception of the first five cycles of movement, the values of the coefficients of friction after 50 cycles of movement are representative values. Consequently, further analyses are based on the data at 50 cycles. Values of the static coefficient of friction are used since these are higher than the dynamic values. Both static and dynamic values appear to follow the same basic trends. The change in the coefficient of friction beyond 50 cycles is indicated in the column headed (4)/(2) in Tables 3 and 4, while the ratio of dynamic to static coefficient of friction at 50 cycles is given in the column headed (3)/(2) in Tables 3 and 4.

Test data at 50 cycles from all 60 tests are presented in Figs.10, 11 and 12 in the form of plots of coefficient of friction against contact pressure. Also shown on each plot is the best fit to the data of the relationship given in Eqn.(1). This was found from a linear regression analysis using Eqn.(2). It can be seen that reasonable fits are obtained for the data, particularly that at 20 °C. More scatter is apparent in the data from the tests at -25 °C.

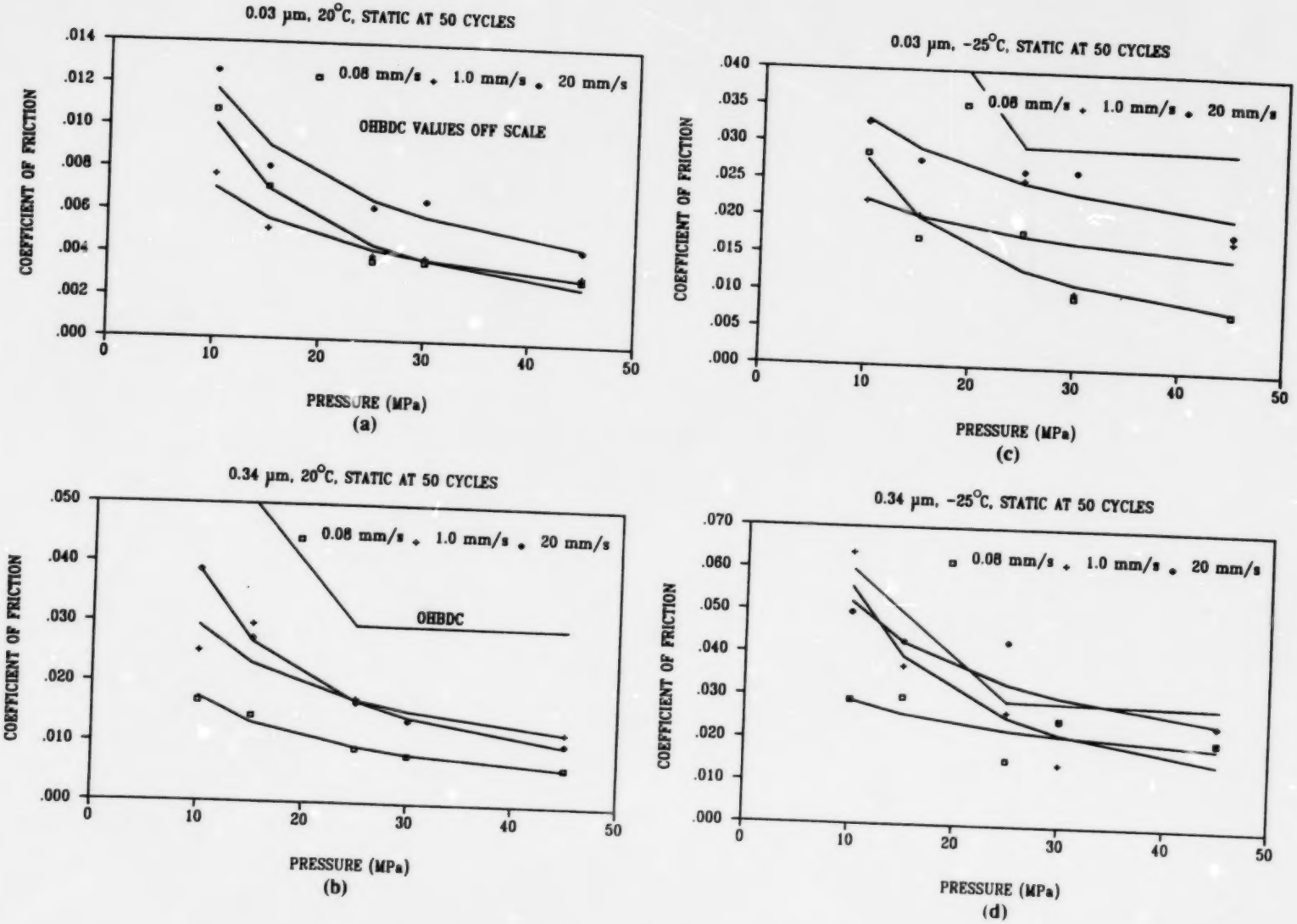
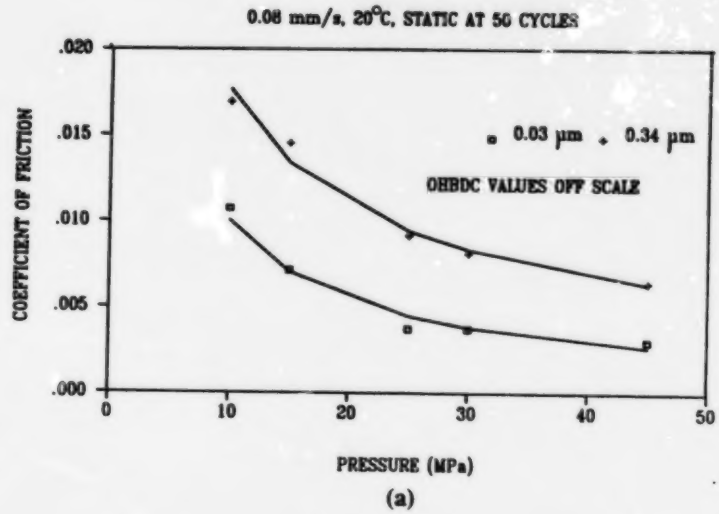
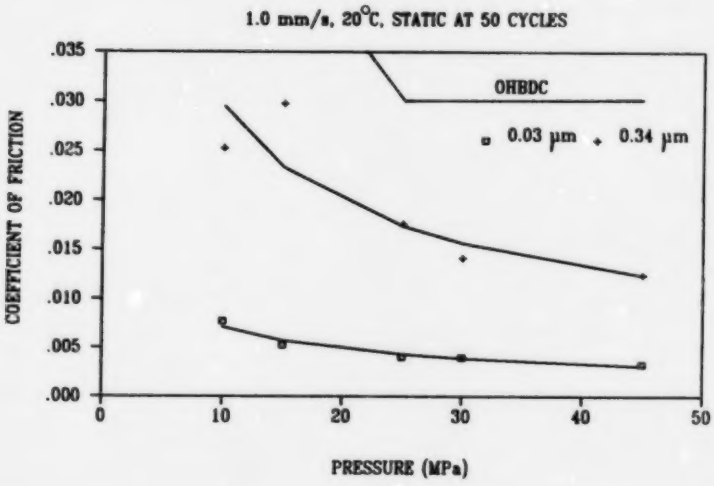


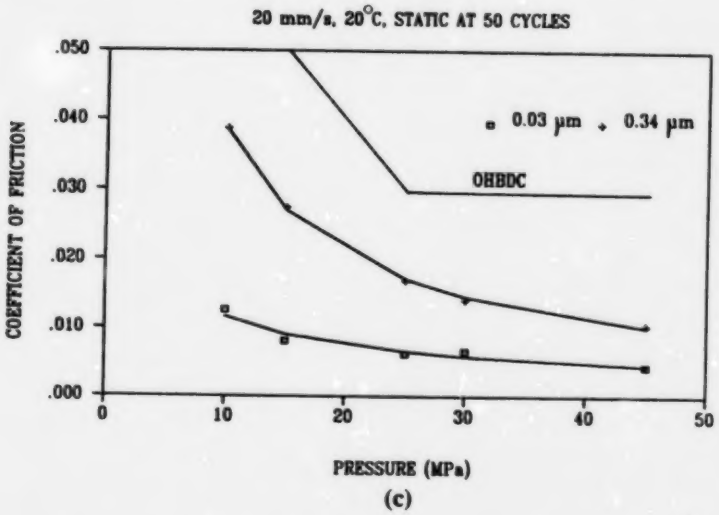
FIG.10 COEFFICIENT OF FRICTION vs. PRESSURE INDICATING THE INFLUENCE OF SLIDING SPEED



(a)

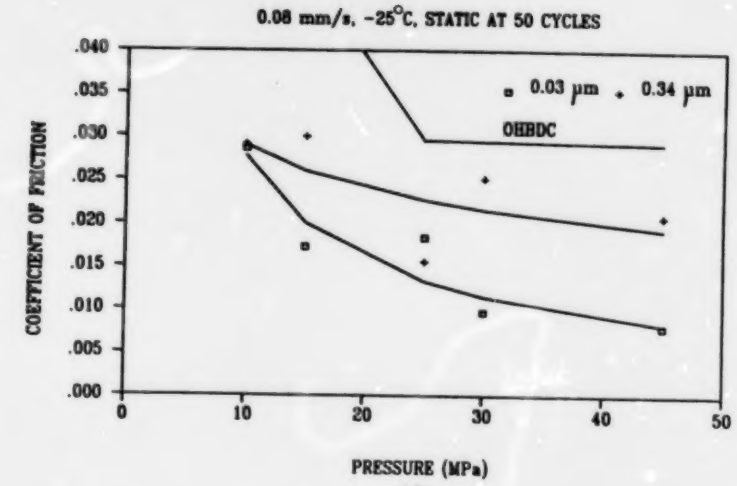


(b)

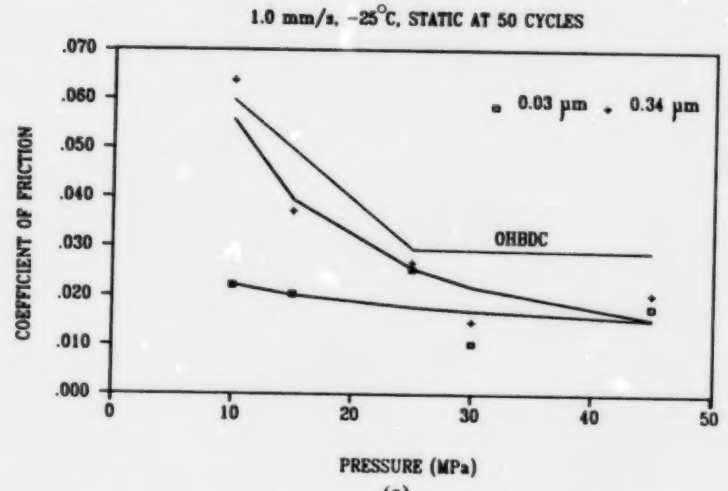


(c)

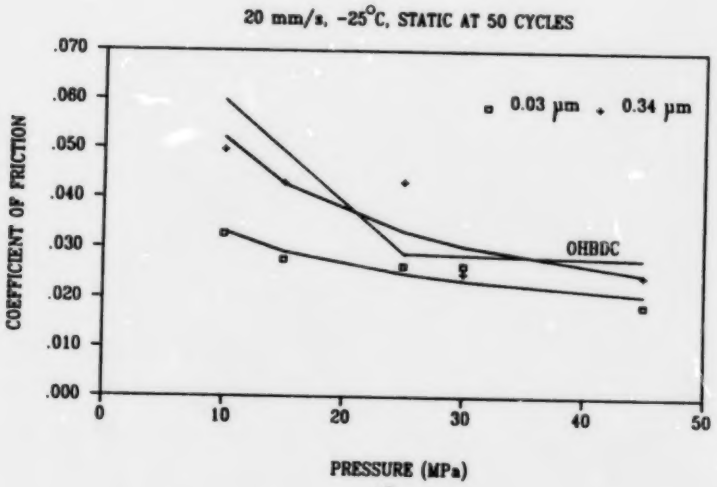
FIG.11 COEFFICIENT OF FRICTION vs. PRESSURE INDICATING THE INFLUENCE OF SURFACE ROUGHNESS



(d)

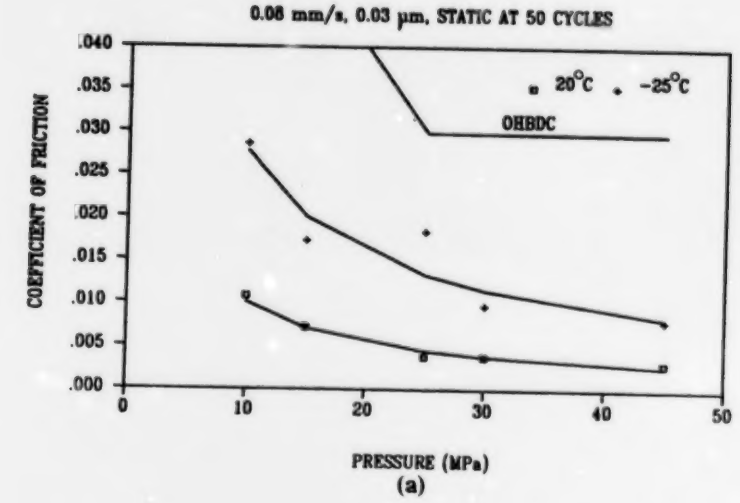


(e)

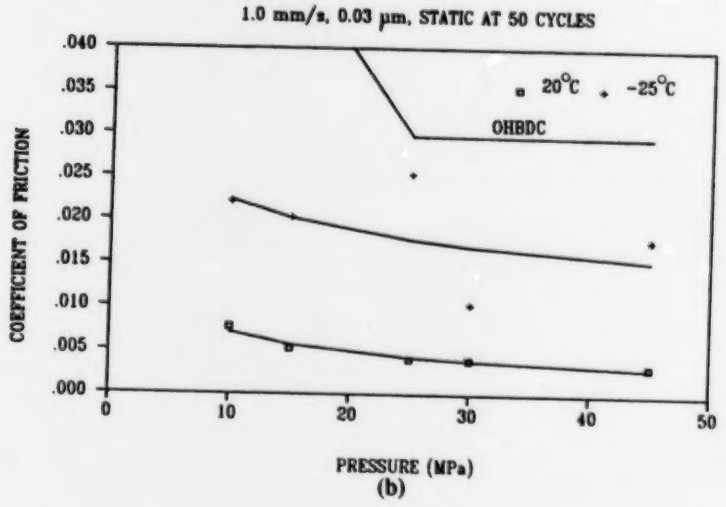


(f)

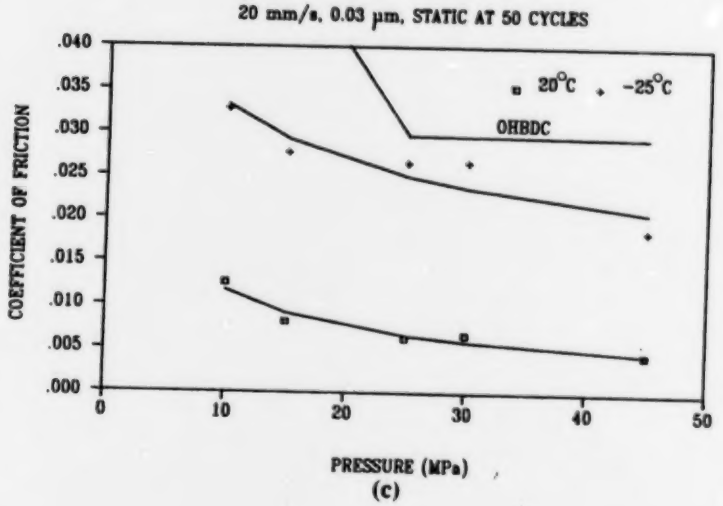
FIG.11 (CONTINUED)



(a)

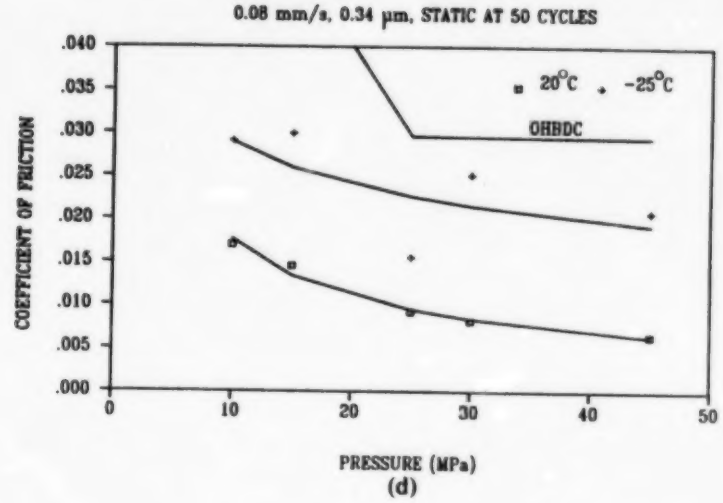


(b)

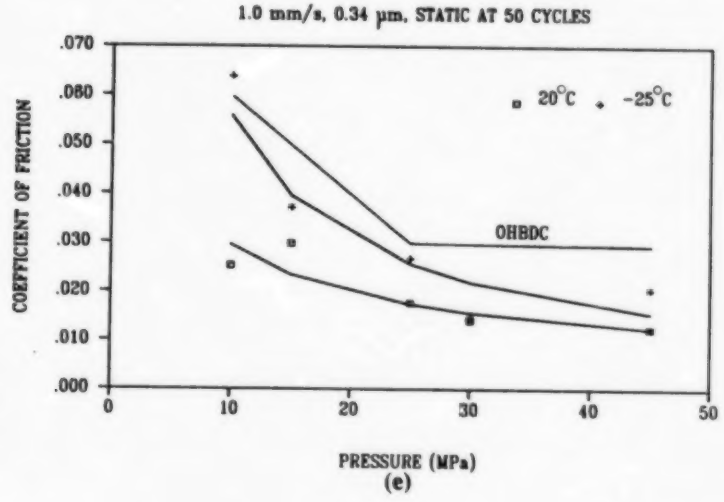


(c)

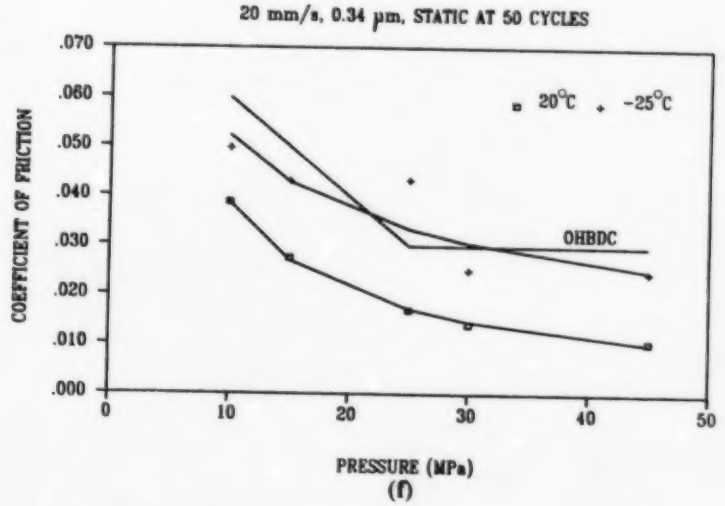
FIG.12 COEFFICIENT OF FRICTION vs. PRESSURE INDICATING THE INFLUENCE OF TEMPERATURE



(d)



(e)



(f)

FIG.12 (CONTINUED)

The influence of speed, for a particular temperature and surface roughness of the stainless steel, is indicated in each of the four plots of Fig.10, while the influence of surface roughness for a particular temperature and sliding speed, and the influence of temperature for a particular sliding speed and surface roughness are indicated in each of the six plots of Figs.11 and 12, respectively. Values of the coefficient of friction specified for lubricated TFE sliding surfaces in the Ontario Highway Bridge Design Code (OHBDC) [1] are given in Table 5 and the values for unfilled lubricated TFE surface are shown on most of the plots in Figs.10, 11 and 12. The values given for unfilled TFE in the OHBDC decrease with increasing pressure up to 25 MPa, and remain constant at pressures beyond 25 MPa.

TABLE 5 COEFFICIENT OF FRICTION FOR LUBRICATED TFE SLIDING SURFACES [1]

Contact Pressure (MPa)	Coefficient of Friction	
	Unfilled	Filled
10	0.06	0.12
15	0.05	0.10
20	0.04	0.08
25	0.03	0.07
30 and above	0.03	0.06

All the plots in Figs. 10, 11 and 12 show the established trend in that the coefficient of friction of TFE decreases with increasing pressure under all conditions.

Figure 10 reflects the general trend observed by others that the coefficient of friction increases with sliding speed but it can be seen that this is not the case under all conditions. Figure 10(a), relating to the tests at 20 °C using No.8 finish stainless steel, indicates that the coefficient of friction at 0.08 mm/s is greater than that at 1 mm/s at pressures below 25 MPa, while Fig.10(d), relating to the tests at -25 °C using No.4 finish stainless steel, shows that the coefficient of friction at 1 mm/s is the highest at low pressure (10 MPa) but the lowest at high pressure (45 MPa). Further, it can be seen in Fig.10 that all measured values of the coefficient of friction are less than the specified values for unfilled TFE in the OHBDC [1], with the exception of those from the high speed (20 mm/s) test (Fig.10(d)) using the No.4 stainless steel plate at -25 °C in the pressure range from 20 to 30 MPa.

Figure 11 shows that the coefficient of friction is higher for the rougher (No.4 finish) stainless steel for all conditions. However, it appears that the difference between the values for the two finishes (No.4 and No.8) is less at -25 °C than at 20 °C, particularly at higher speeds. Figure 11(f) indicates that the measured coefficient of friction exceeds the OHBDC value in the 20 to 30 MPa range at -25 °C with a No.4 finish stainless steel plate. However, this finish (0.34 μm) is rougher than the 0.25 μm finish permitted by the OHBDC.

Figure 12 shows that the coefficient of friction is larger at -25 °C than at 20 °C for all conditions, but the difference appears to be less pronounced for the No.4 finish. Again Fig.12(f) shows that the OHBDC value of the coefficient of friction is exceeded at -25 °C for the No.4 finish stainless steel in the 20 to 30 MPa range.

The column headed (1)/(2) in Tables 3 and 4 shows that the ratio of the initial coefficient of friction to that at 50 cycles is not dependent on contact pressure. It can be seen that this ratio increases with sliding speed and can be as high as five at 20 mm/s. The ratios in column (4)/(2) of Tables 3 and 4 indicate in most cases an increase in the coefficient of friction beyond 50 cycles. From column (3)/(2) it can be seen that the ratio of the dynamic to static friction at 50 cycles varies from an average of 0.54 in Series 2 to 0.88 in Series 12. This ratio appears to be independent of contact pressure.

4.5 EVALUATION OF PARAMETERS

Two parameters, Q and n, are used in Eqn.(1) to relate the coefficient of friction and the contact pressure. A value of each of these two parameters was determined from the data for each of the twelve series of tests using a linear regression analysis and the relationship of Eqn.(2). One value of each parameter was obtained from each series. These values are presented in Figs. 13 and 14, which show plots of Q and n, respectively, against speed of travel for the two temperatures and roughnesses of the stainless steel. Only three data points are obtained for each plot and consequently, it is not possible at this stage to develop general relationships for the variations of Q and n with speed for the two conditions of temperature and roughness of stainless steel. Additional test data must be generated. However, it should be noted in Figs. 13(a) and 14(a), that the values for Q and n for 20 °C and 0.03 μm are in the range of the values, namely Q = 0.06 and n = 0.38, given in Fig.3 for a lubricated surface with a 0.05 μm finish.

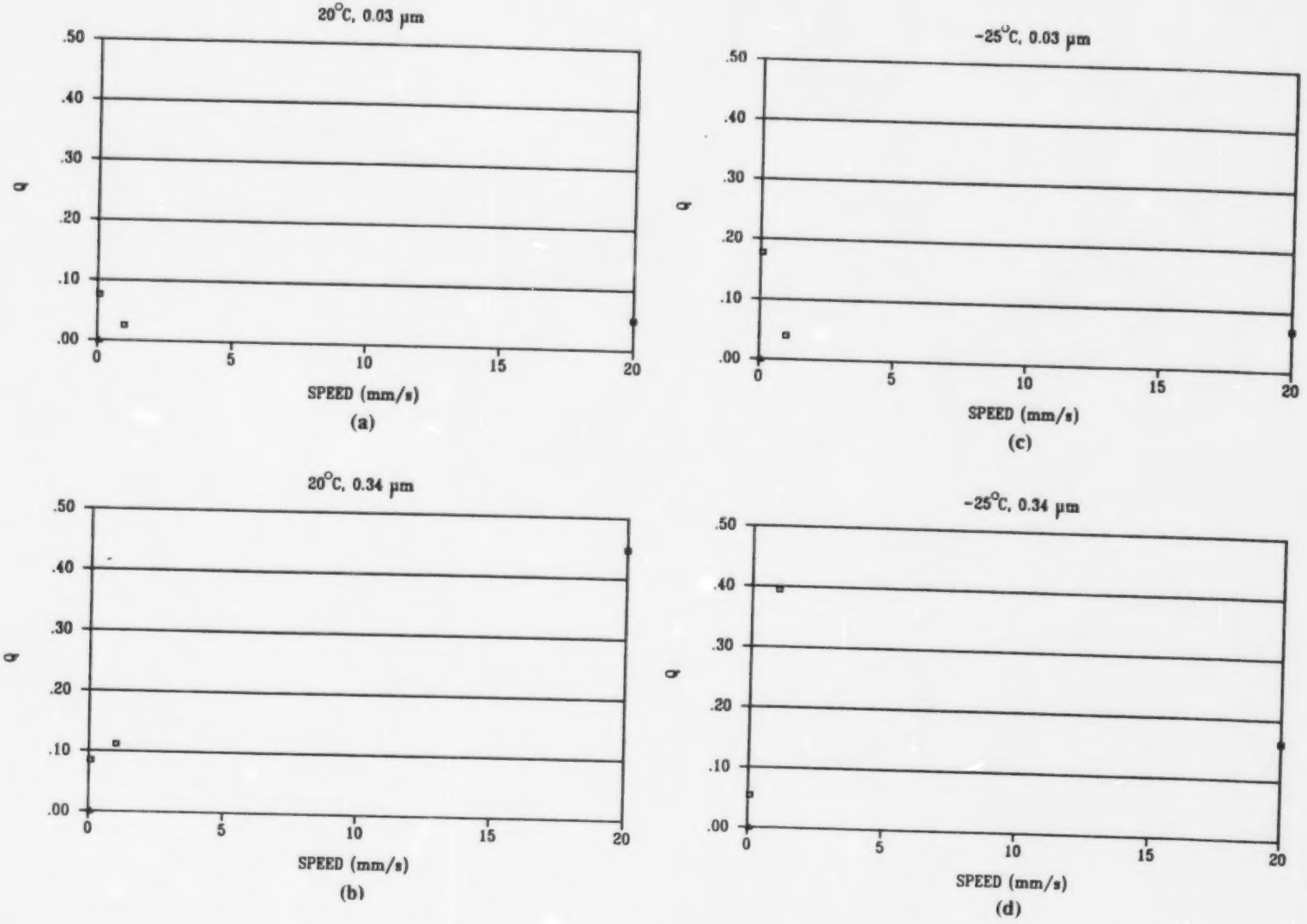


FIG.13 Q vs. SPEED OF TRAVEL

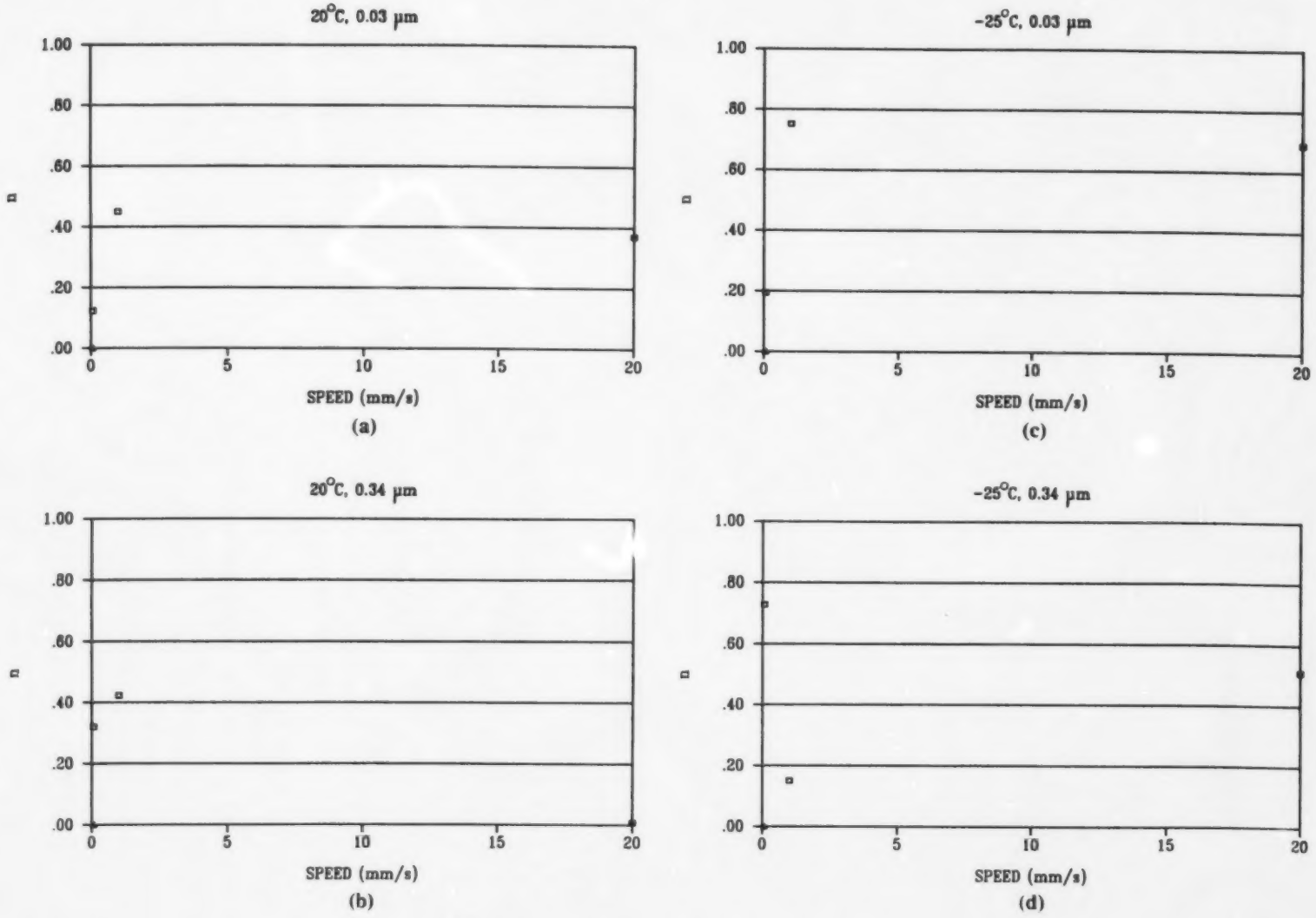


FIG.14 n vs. SPEED OF TRAVEL

5. RECOMMENDATIONS FOR DESIGN AND FURTHER RESEARCH

Recommendations regarding the coefficient of friction to be used in establishing the frictional force in a TFE sliding surface in a bridge bearing are made in this chapter. Further research required to refine these recommendations is outlined.

Figures 10, 11 and 12 show that the values of the coefficient of friction for unfilled TFE, as given by the OHBDC, are higher than those obtained after 50 cycles for all conditions simulated in the test program, with the exception of the high speed tests at low temperature using a rough stainless steel plate in the 20 to 30 MPa range. Since smooth (No.8 finish) stainless steel is normally used for bearings manufactured in Ontario, the OHBDC values may be considered as conservative for temperatures as low as -25 °C and sliding speeds up to 20 mm/s, provided that it is permissible to design structures for the static coefficient of friction at 50 cycles.

Table 6 shows a comparison between the values of the initial coefficient of friction from the smooth plate tests and those specified in the OHBDC. It can be seen that, if structures are to be designed for the initial level of friction, then the OHBDC values are unconservative at -25 °C and 20 mm/s (Series 9 tests). The initial coefficient of friction under these conditions may be as high 2.8 times the OHBDC value.

The tests have indicated that the coefficient of friction decreases rapidly during the first few cycles of movement and changes little between 5 and 50 cycles. Consequently, it appears that significant benefits, in the form of a reduction in the specified coefficient of friction for design, could be achieved if the initial coefficient of friction of TFE could be reduced. This could be achieved presumably by subjecting the sliding surface to cyclic movement prior to installation of a bearing.

Two problems are envisaged with this approach. Firstly, a facility with a large load capacity would be required to cycle at service load level the range of bearings manufactured. Secondly, the effect of dwell of load, where if cycling is discontinued for a period of time the coefficient of friction increases, may counteract any advantage gained from precycling. The first problem may not be significant since the test data indicate that, although the coefficient of friction is dependent on pressure, the ratio of the initial coefficient of friction to that at 50 cycles is not (see column (1)/(2) in Tables 3 and 4). As a result it may be necessary to load the bearing only to a low level for the initial cycling. This requires further study. With regard to the second problem, the effects of dwell of load are not well documented in the literature and it is suggested that this be studied further.

Other possible means of reducing the initial coefficient of friction should also be explored. One possibility may be to lubricate the stainless steel plate outside the area which is in initial contact with the TFE. A disadvantage of this may be the potential to attract contamination to the lubricant if the sliding surface is not protected from the environment. The influence of contamination of the lubricant on the coefficient of friction of a lubricated TFE-stainless steel interface should be studied.

TABLE 6 COMPARISON OF TEST AND OHBDC VALUES FOR THE COEFFICIENT OF FRICTION

Test No.	Coefficient of Friction		Initial/OHBDC
	Initial	OHBDC	
1-10	0.0116	0.06	0.193
1-15	0.0135	0.05	0.270
1-25	0.0058	0.03	0.193
1-30	0.0055	0.03	0.183
1-45		0.03	
2-10	0.0136	0.06	0.227
2-15	0.0140	0.05	0.280
2-25		0.03	
2-30		0.03	
2-45	0.0086	0.03	0.287
3-10	0.0334	0.06	0.557
3-15	0.0473	0.05	0.946
3-25	0.0338	0.03	1.127
3-30	0.0290	0.03	0.967
3-45	0.0230	0.03	0.767
7-10	0.0603	0.06	1.005
7-15	0.0232	0.05	0.464
7-25	0.0225	0.03	0.750
7-30	0.0143	0.03	0.477
7-45	0.0084	0.03	0.280
8-10	0.0549	0.06	0.915
8-15	0.0387	0.05	0.774
8-25	0.0576	0.03	1.920
8-30	0.0229	0.03	0.763
8-45	0.0537	0.03	1.790
9-10	0.1000	0.06	1.667
9-15	0.1120	0.05	2.240
9-25	0.0809	0.03	2.697
9-30	0.0844	0.03	2.813
9-45	0.0590	0.03	1.967

Tables 3 and 4 (column (1)/(2)) show that ratio of the initial coefficient of friction to that at 50 cycles increases with sliding speed. Sliding speeds at the bearings of typical types of bridge structure should be determined from field tests in order to establish upper limits for the sliding speed.

Significant wear of the TFE was observed in the low temperature, high speed tests using No.8 finish stainless steel plate. Since this finish is normally used in bearings in Ontario, the phenomenon of wear of the TFE should be studied further.

6. CONCLUSIONS

Based on the values of the coefficient of static friction of TFE after 50 cycles of movement, unless otherwise stated, the following conclusions may be drawn from this test program:

1) The coefficient of friction decreases with increasing pressure over the range 10 MPa to 45 MPa.

2) The general trend is an increase in the coefficient of friction with sliding speed over the range 0.08 mm/s to 20 mm/s.

3) The coefficient of friction increases with roughness of the stainless steel plate over the range 0.03 μm to 0.34 μm.

4) The coefficient of friction increases with decrease in temperature over the range 20 °C to -25 °C.

5) Values of the coefficient of friction given for unfilled TFE in the OHBDC indicate the proper trend and are conservative except for the rough stainless steel plate at -25 °C and a travel speed of 20 mm/s.

6) The initial coefficient of friction can be as high as five times that after 50 cycles of movement.

7) The coefficient of friction decreases rapidly during the first five cycles of movement, remains fairly constant up to 50 cycles, increases from 50 to 1000 cycles and then again remains fairly constant up to as many as 10000 cycles.

8) The dynamic coefficient of friction is lower than the static coefficient but follows the same trend with increasing number of cycles.

9) The relationship of Eqn.(1) gives a reasonably good fit to the test data but more data are required in order to establish values of the parameters Q and n.

10) Possible means of reducing the initial coefficient of friction should be explored.

REFERENCES

1. "Ontario Highway Bridge Design Code", Ministry of Transportation and Communications, Second Edition, Downsview, Ontario, 1983.

2. Manning, D.G., and Bassi, K.G., "Bridge Bearing Performance in Ontario", Joint Sealing and Bearing Systems for Concrete Structures, ACI Publication SP-94, Vol.2, 1986, pp 1017-1040.

3. Campbell, T.I. and Kong, W.L., "TFE Sliding Surfaces in Bridge Bearings", Report ME-87-06 Ministry of Transportation and Communications of Ontario, July 1987, 57 pp.

4. Hakenjos, V. and Richter, K., "Experiments with Sliding Supports", from Lager im Bauwesen (Eggert, H., Grote, J. and Kauschke, W.) Wilhelm Ernst & Sohn, Berlin/Munchen/Dusseldorf, 1974, pp 301-309.

5. Taylor, M.E., "PTFE in Highway Bridge Bearings", Report No. TRRL-LR491, Transport and Road Research Laboratory, Crowthorne, England, 1972, 62 pp.

6. Price, W.I.J., "Transmission of Horizontal Forces and Movements by Bridge Bearings", Joint Sealing and Bearing Systems for Concrete Structures, ACI Publication SP-70, Vol.2, 1982, pp 761-784.

7. Long, J.E., "The Performance of PTFE in Bridge Bearings", Civil Engineering and Public Works Review, Vol.64, May 1969, pp 459-462.

8. OPSS 1203 "Material Specification for Bearings-Rotational and Sliding Surface", Ontario Provincial Standard Specification, July 1988.

9. "Silicone Compound, NATO Code No. S-736", US Military Specification, MIL-S-8660C, September 1983.

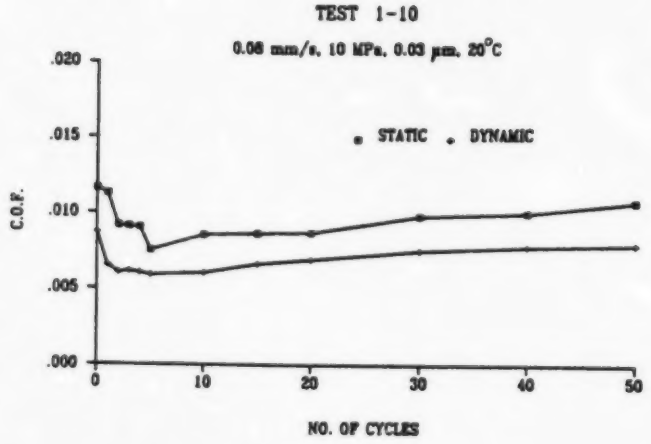
10. ASTM A480-82a "Standard Specification for General Requirements for Flat-Rolled Stainless and Heat-Resisting Steel Plate, Sheet, and Strip", American Society for Testing and Materials, 1982.

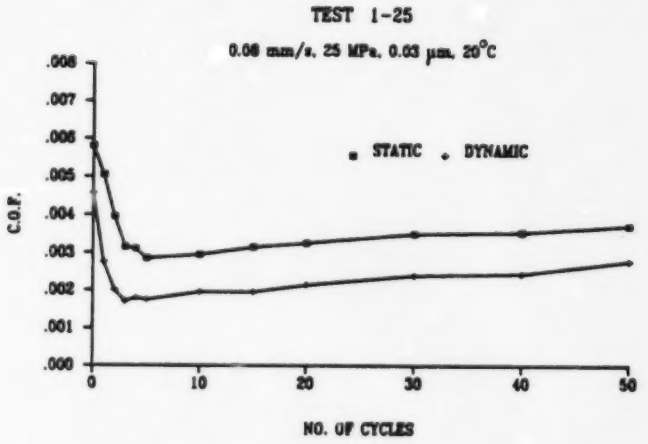
11. American Association of State Highway and Transportation Officials, "Standard Specifications for Highway Bridges", 13th Edition, Washington D.C., 1983.

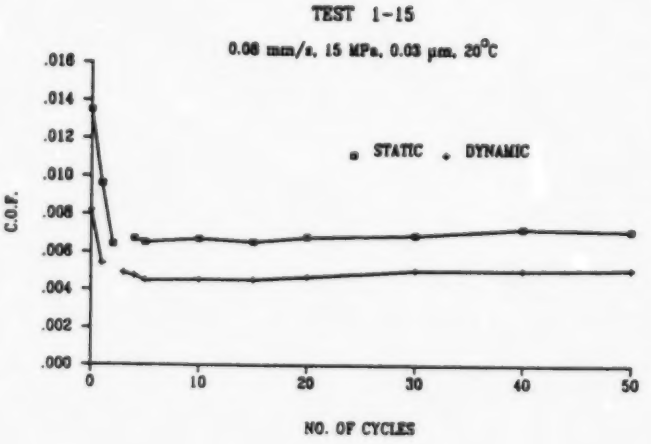
APPENDIX A

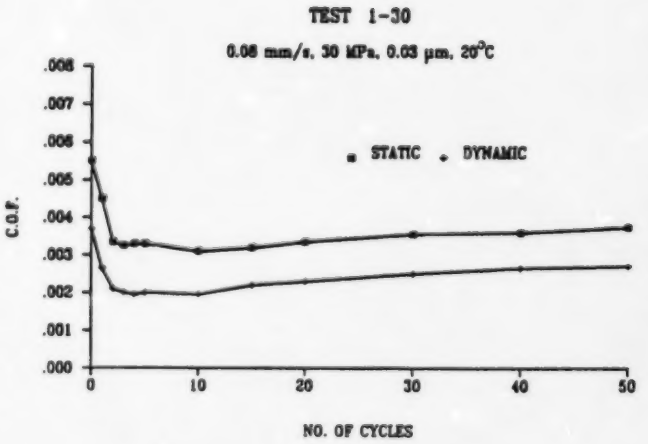
PLOTS OF COEFFICIENT OF FRICTION (C.O.F.)

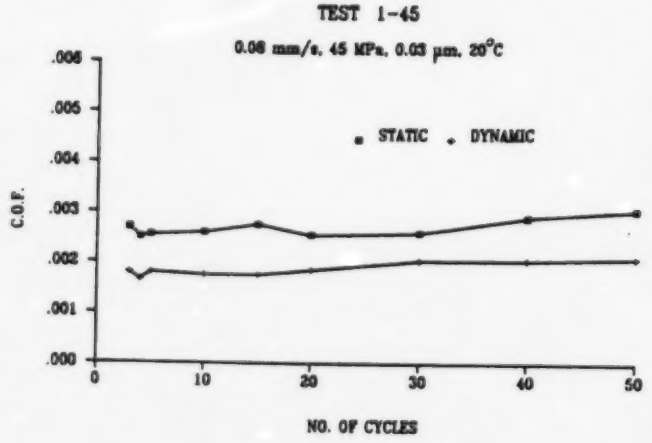
VERSUS NUMBER OF CYCLES FOR ALL SIXTY TESTS

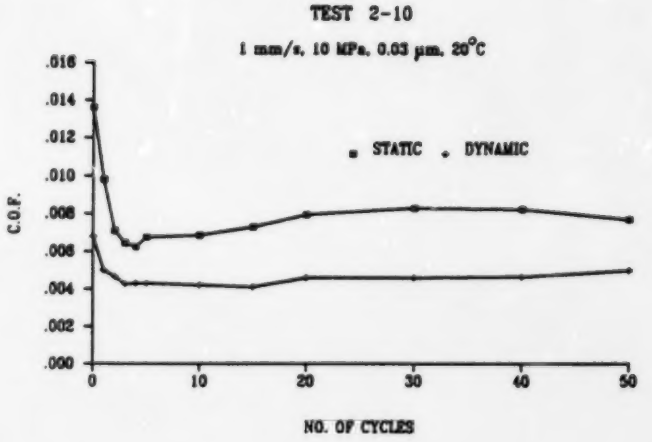

TEST 1-10
0.06 mm/s, 10 MPa, 0.03 μm, 20°C
STATIC
DYNAMIC
C.O.F.
.020
.015
.010
.005
.000
0
10
20
30
40
50
NO. OF CYCLES

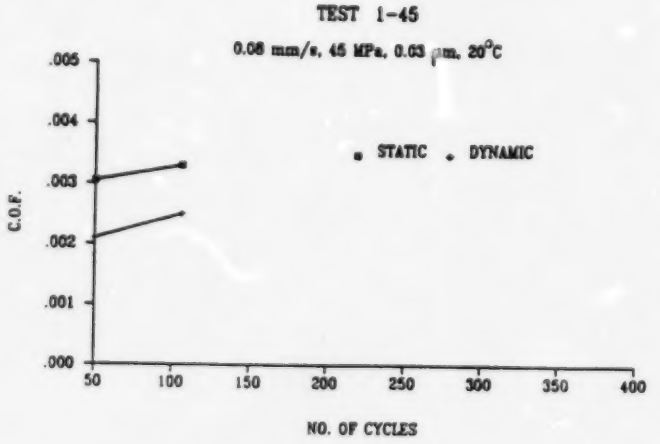

TEST 1-25
0.06 mm/s, 25 MPa, 0.03 μm, 20°C
STATIC
DYNAMIC
C.O.F.
.008
.007
.006
.005
.004
.003
.002
.001
.000
0
10
20
30
40
50
NO. OF CYCLES

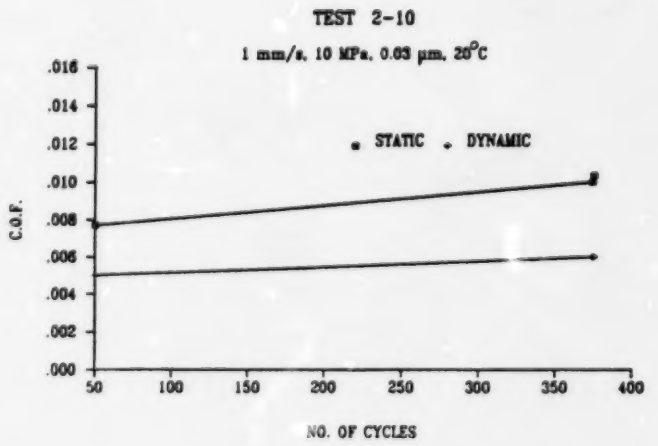

TEST 1-15
0.06 mm/s, 15 MPa, 0.03 μm, 20°C
STATIC
DYNAMIC
C.O.F.
.016
.014
.012
.010
.008
.006
.004
.002
.000
0
10
20
30
40
50
NO. OF CYCLES


TEST 1-30
0.06 mm/s, 30 MPa, 0.03 μm, 20°C
STATIC
DYNAMIC
C.O.F.
.008
.007
.006
.005
.004
.003
.002
.001
.000
0
10
20
30
40
50
NO. OF CYCLES


TEST 1-45
0.08 mm/s, 45 MPa, 0.03 μm, 20°C
■ STATIC ◆ DYNAMIC
C.O.F.
.006
.005
.004
.003
.002
.001
.000
0
10
20
30
40
50
NO. OF CYCLES

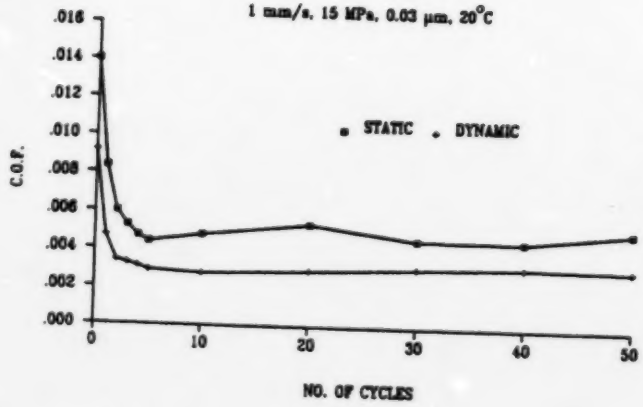

TEST 2-10
1 mm/s, 10 MPa, 0.03 μm, 20°C
■ STATIC ◆ DYNAMIC
C.O.F.
.016
.014
.012
.010
.008
.006
.004
.002
.000
0
10
20
30
40
50
NO. OF CYCLES


TEST 1-45
0.08 mm/s, 45 MPa, 0.03 μm, 20°C
■ STATIC ◆ DYNAMIC
C.O.F.
.005
.004
.003
.002
.001
.000
50
100
150
200
250
300
350
400
NO. OF CYCLES


TEST 2-10
1 mm/s, 10 MPa, 0.03 μm, 20°C
■ STATIC ◆ DYNAMIC
C.O.F.
.016
.014
.012
.010
.008
.006
.004
.002
.000
50
100
150
200
250
300
350
400
NO. OF CYCLES

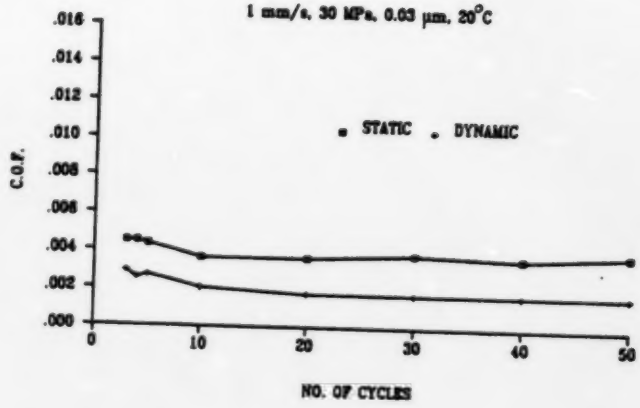
TEST 2-15

1 mm/s, 15 MPa, 0.03 μm, 20°C



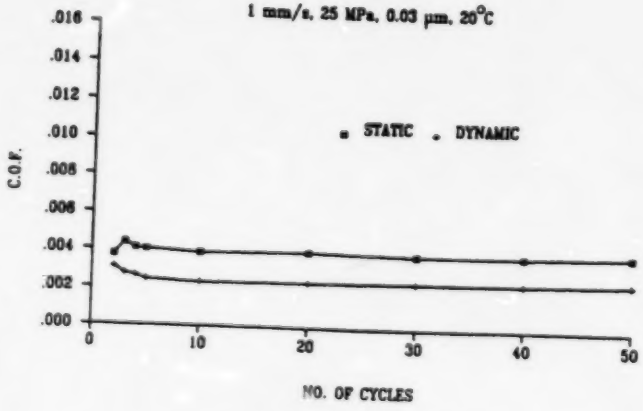
TEST 2-30

1 mm/s, 30 MPa, 0.03 μm, 20°C



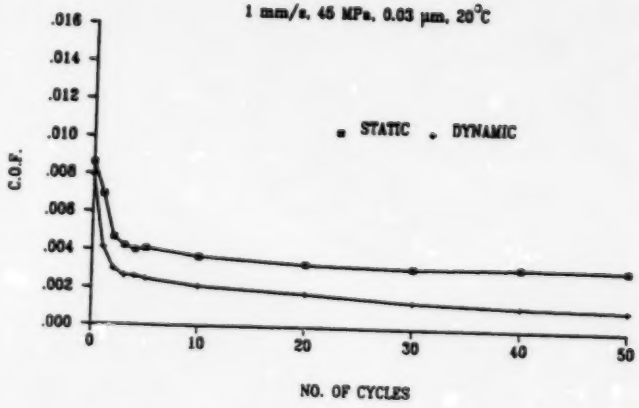
TEST 2-25

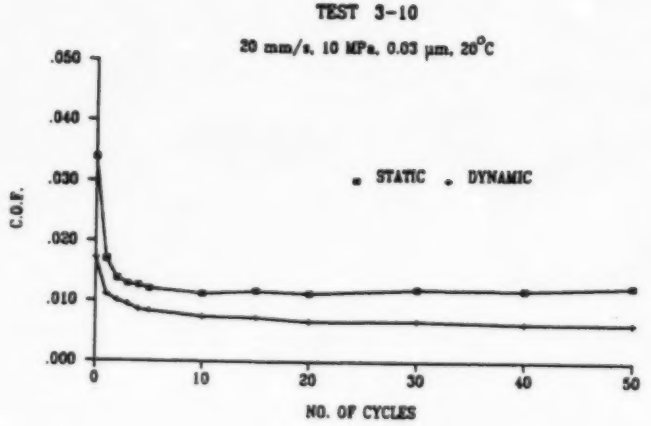
1 mm/s, 25 MPa, 0.03 μm, 20°C

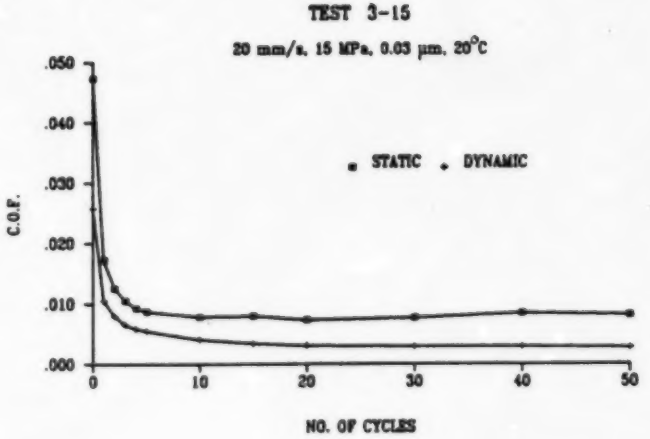


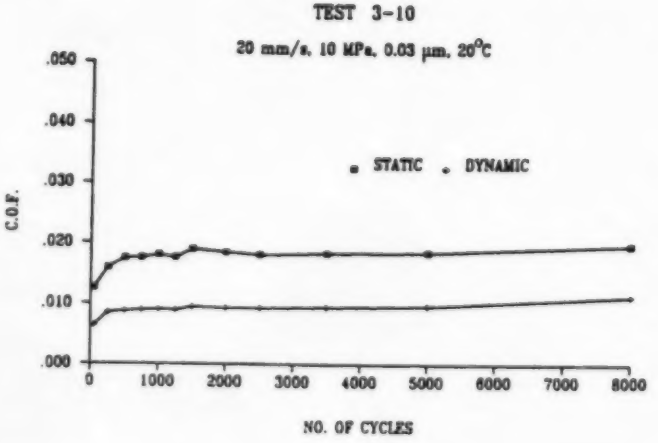
TEST 2-45

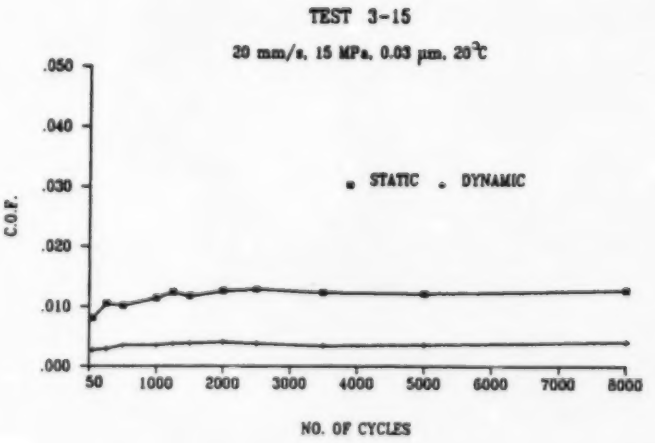
1 mm/s, 45 MPa, 0.03 μm, 20°C




TEST 3-10
20 mm/s, 10 MPa, 0.03 μm, 20°C
STATIC
DYNAMIC
C.O.F.
.050
.040
.030
.020
.010
.000
0
10
20
30
40
50
NO. OF CYCLES

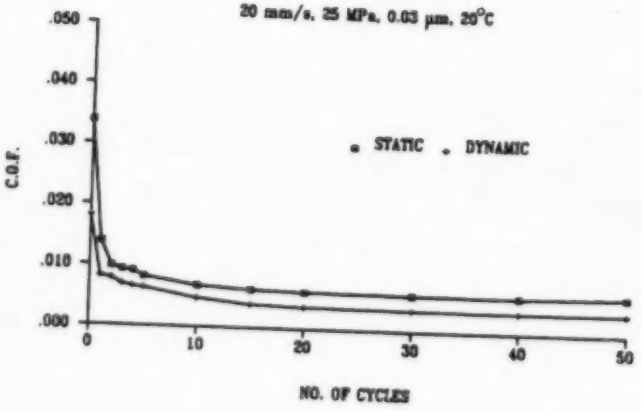

TEST 3-15
20 mm/s, 15 MPa, 0.03 μm, 20°C
STATIC
DYNAMIC
C.O.F.
.050
.040
.030
.020
.010
.000
0
10
20
30
40
50
NO. OF CYCLES


TEST 3-10
20 mm/s, 10 MPa, 0.03 μm, 20°C
STATIC
DYNAMIC
C.O.F.
.050
.040
.030
.020
.010
.000
0
1000
2000
3000
4000
5000
6000
7000
8000
NO. OF CYCLES


TEST 3-15
20 mm/s, 15 MPa, 0.03 μm, 20°C
STATIC
DYNAMIC
C.O.F.
.050
.040
.030
.020
.010
.000
50
1000
2000
3000
4000
5000
6000
7000
8000
NO. OF CYCLES

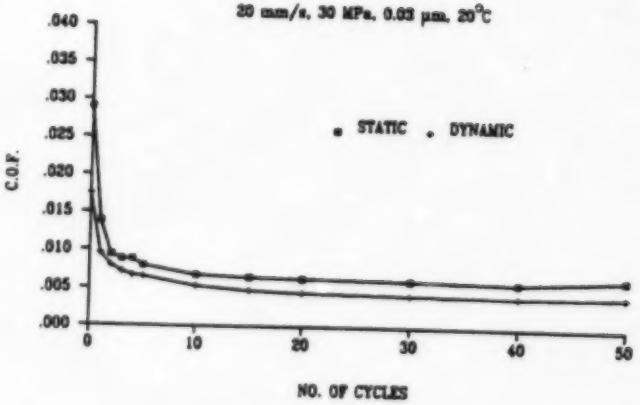
TEST 3-25

20 mm/s, 25 MPa, 0.03 μm, 20°C



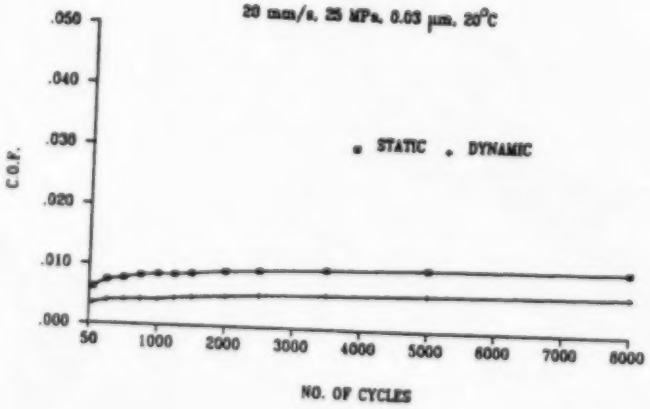
TEST 3-30

20 mm/s, 30 MPa, 0.03 μm, 20°C



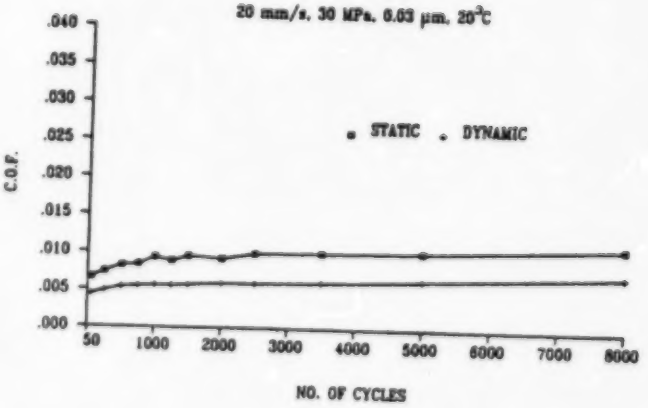
TEST 3-25

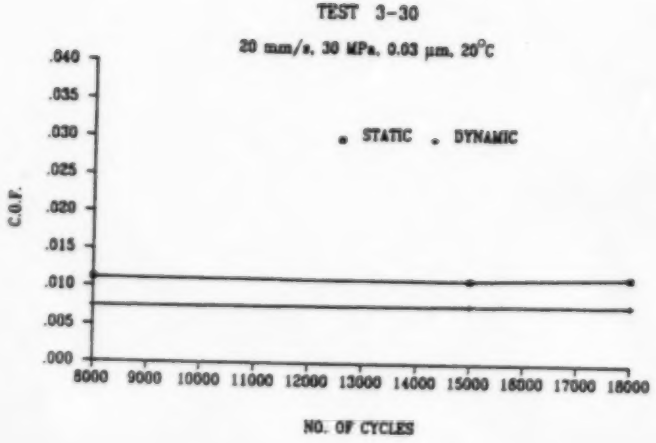
20 mm/s, 25 MPa, 0.03 μm, 20°C

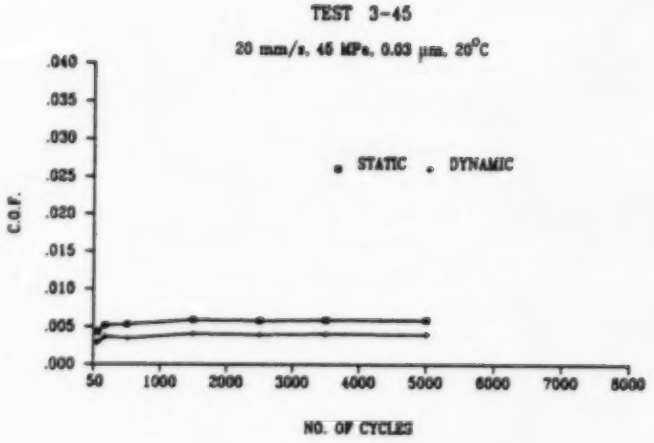


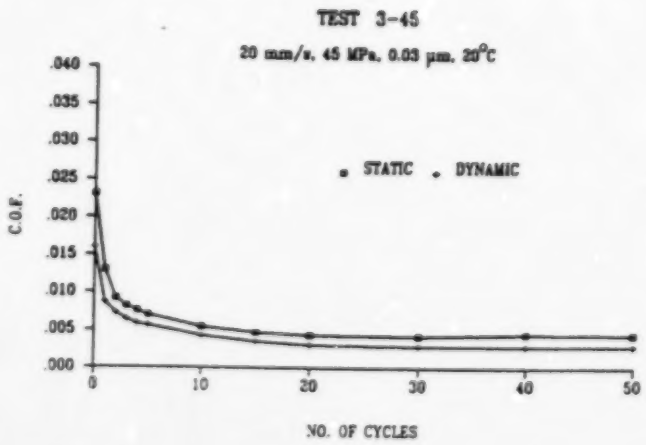
TEST 3-30

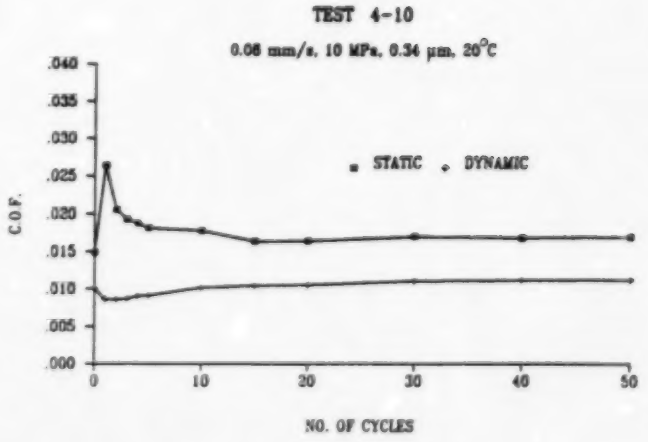
20 mm/s, 30 MPa, 0.03 μm, 20°C

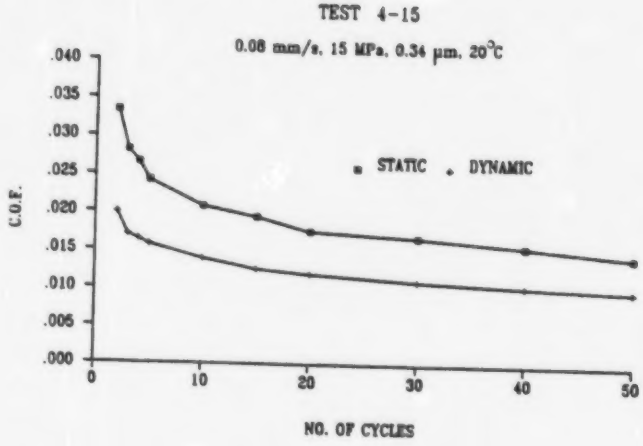


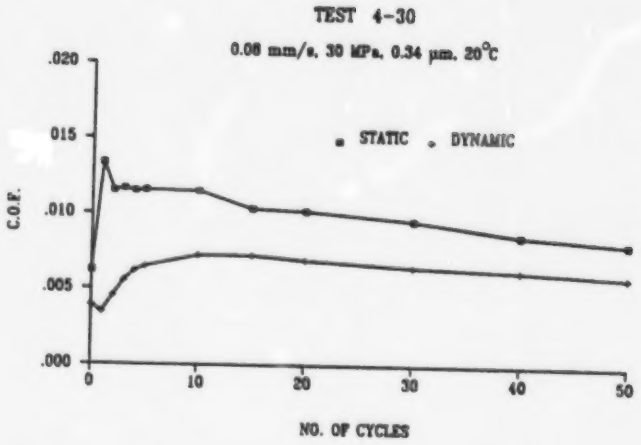

TEST 3-30
20 mm/s, 30 MPa, 0.03 μm, 20°C
STATIC
DYNAMIC
C.O.F.
.040
.035
.030
.025
.020
.015
.010
.005
.000
8000 9000 10000 11000 12000 13000 14000 15000 16000 17000 18000
NO. OF CYCLES

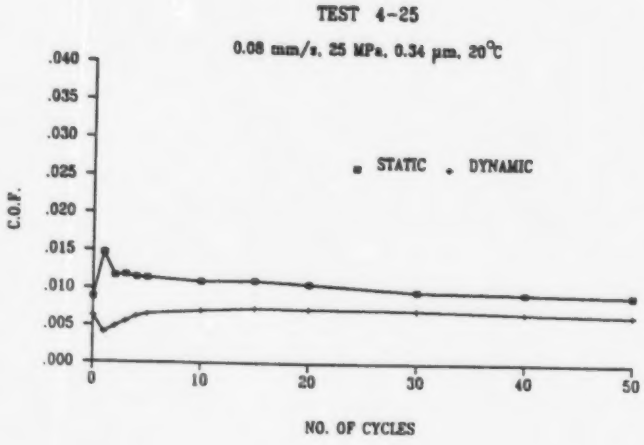

TEST 3-45
20 mm/s, 45 MPa, 0.03 μm, 20°C
STATIC
DYNAMIC
C.O.F.
.040
.035
.030
.025
.020
.015
.010
.005
.000
50 1000 2000 3000 4000 5000 6000 7000 8000
NO. OF CYCLES

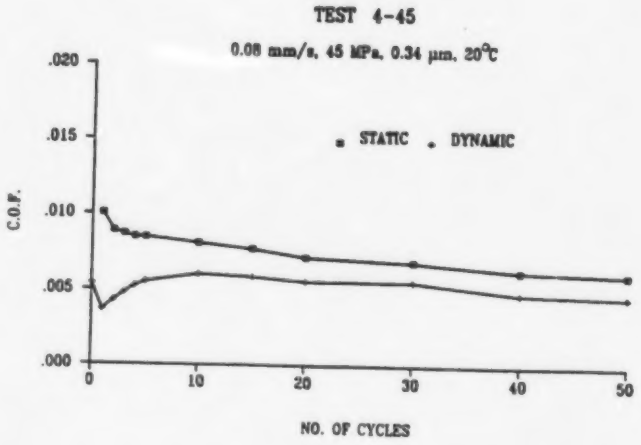

TEST 3-45
20 mm/s, 45 MPa, 0.03 μm, 20°C
STATIC
DYNAMIC
C.O.F.
.040
.035
.030
.025
.020
.015
.010
.005
.000
0 10 20 30 40 50
NO. OF CYCLES

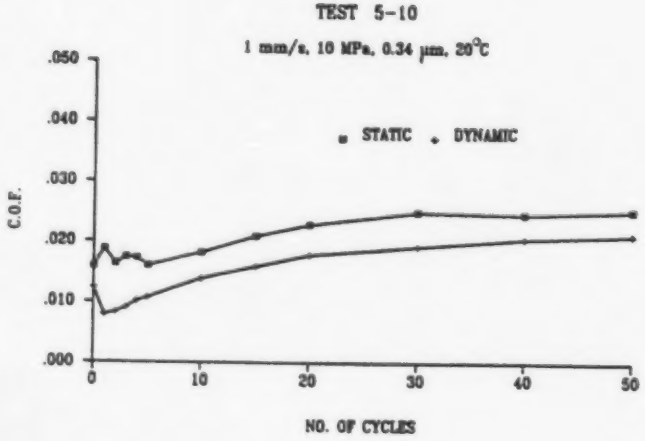

TEST 4-10
0.06 mm/s, 10 MPa, 0.34 μm, 20°C
STATIC
DYNAMIC
C.O.F.
.040
.035
.030
.025
.020
.015
.010
.005
.000
0 10 20 30 40 50
NO. OF CYCLES

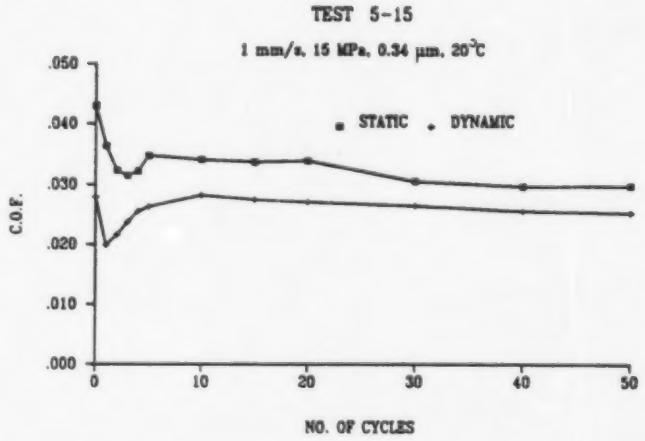

TEST 4-15
0.08 mm/s, 15 MPa, 0.34 μm, 20°C
■ STATIC ◆ DYNAMIC
C.O.F.
.040
.035
.030
.025
.020
.015
.010
.005
.000
0
10
20
30
40
50
NO. OF CYCLES

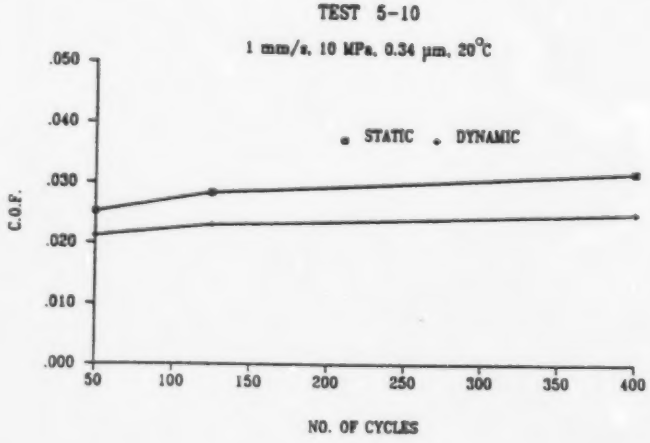

TEST 4-30
0.08 mm/s, 30 MPa, 0.34 μm, 20°C
■ STATIC ◆ DYNAMIC
C.O.F.
.020
.015
.010
.005
.000
0
10
20
30
40
50
NO. OF CYCLES

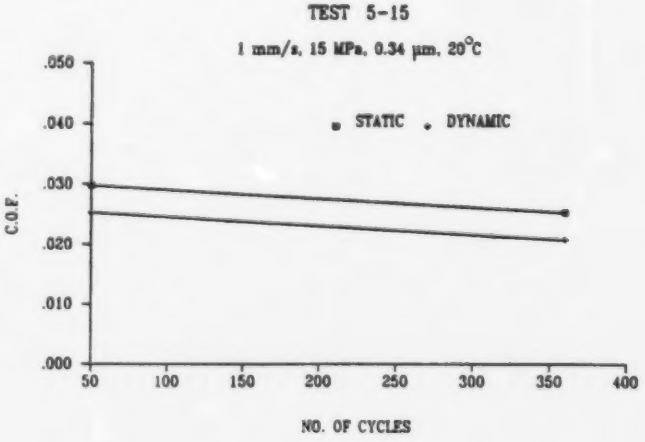

TEST 4-25
0.08 mm/s, 25 MPa, 0.34 μm, 20°C
■ STATIC ◆ DYNAMIC
C.O.F.
.040
.035
.030
.025
.020
.015
.010
.005
.000
0
10
20
30
40
50
NO. OF CYCLES

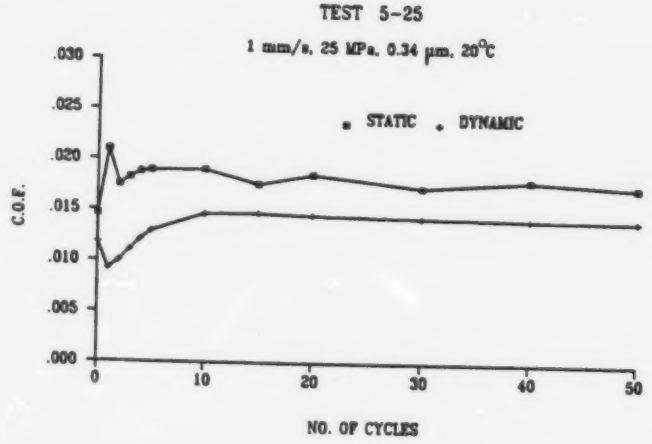

TEST 4-45
0.08 mm/s, 45 MPa, 0.34 μm, 20°C
■ STATIC ◆ DYNAMIC
C.O.F.
.020
.015
.010
.005
.000
0
10
20
30
40
50
NO. OF CYCLES

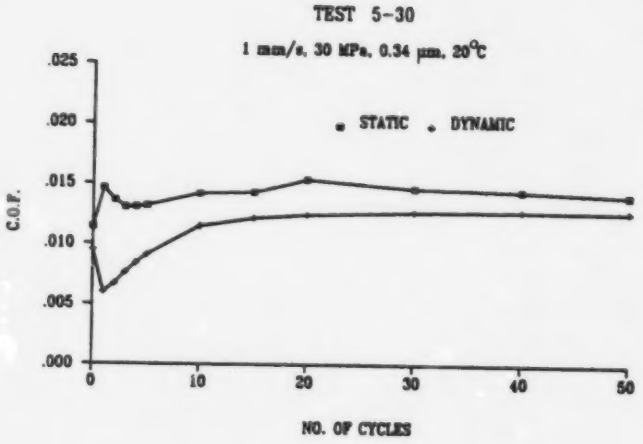

TEST 5-10
1 mm/s, 10 MPa, 0.34 μm, 20°C
■ STATIC ◆ DYNAMIC
C.O.F.
.050
.040
.030
.020
.010
.000
0
10
20
30
40
50
NO. OF CYCLES

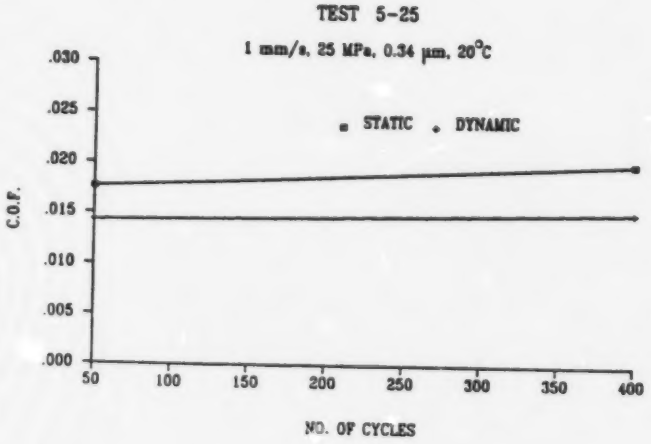

TEST 5-15
1 mm/s, 15 MPa, 0.34 μm, 20°C
■ STATIC ◆ DYNAMIC
C.O.F.
.050
.040
.030
.020
.010
.000
0
10
20
30
40
50
NO. OF CYCLES

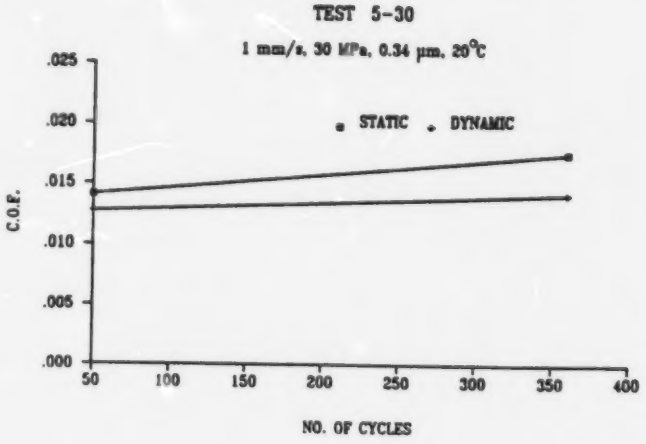

TEST 5-10
1 mm/s, 10 MPa, 0.34 μm, 20°C
■ STATIC ◆ DYNAMIC
C.O.F.
.050
.040
.030
.020
.010
.000
50
100
150
200
250
300
350
400
NO. OF CYCLES

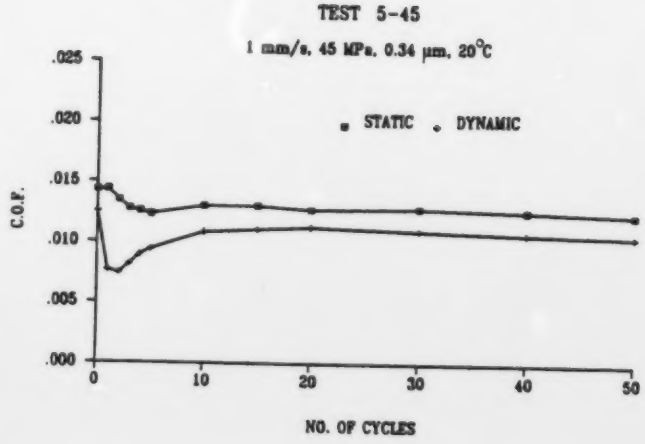

TEST 5-15
1 mm/s, 15 MPa, 0.34 μm, 20°C
■ STATIC ◆ DYNAMIC
C.O.F.
.050
.040
.030
.020
.010
.000
50
100
150
200
250
300
350
400
NO. OF CYCLES

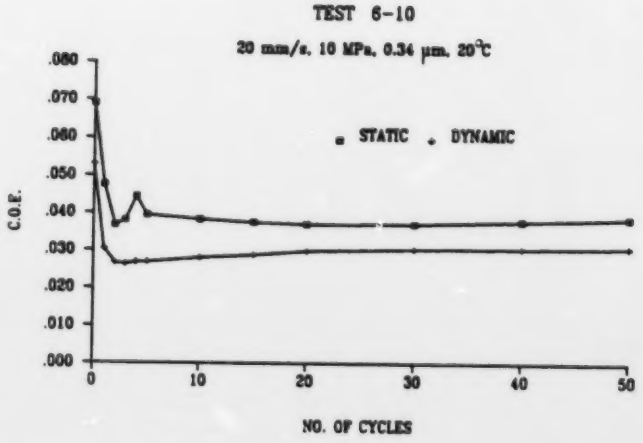

TEST 5-25
1 mm/s, 25 MPa, 0.34 μm, 20°C
▪ STATIC ▪ DYNAMIC
C.O.F.
.030
.025
.020
.015
.010
.005
.000
0
10
20
30
40
50
NO. OF CYCLES

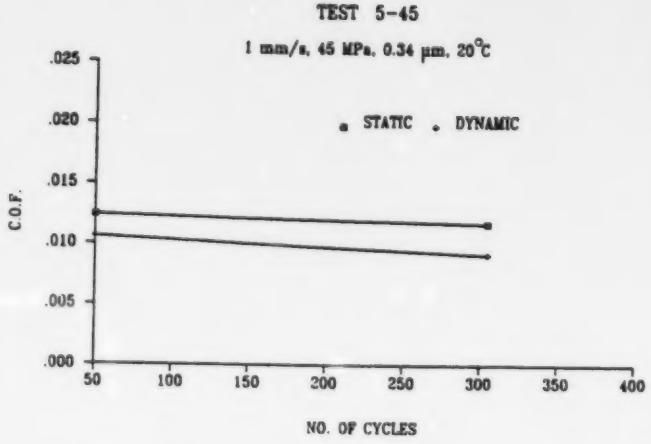

TEST 5-30
1 mm/s, 30 MPa, 0.34 μm, 20°C
▪ STATIC ▪ DYNAMIC
C.O.F.
.025
.020
.015
.010
.005
.000
0
10
20
30
40
50
NO. OF CYCLES

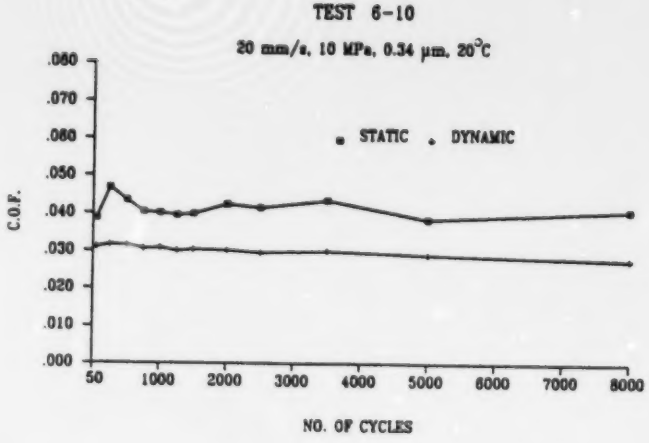

TEST 5-25
1 mm/s, 25 MPa, 0.34 μm, 20°C
▪ STATIC ▪ DYNAMIC
C.O.F.
.030
.025
.020
.015
.010
.005
.000
50
100
150
200
250
300
350
400
NO. OF CYCLES

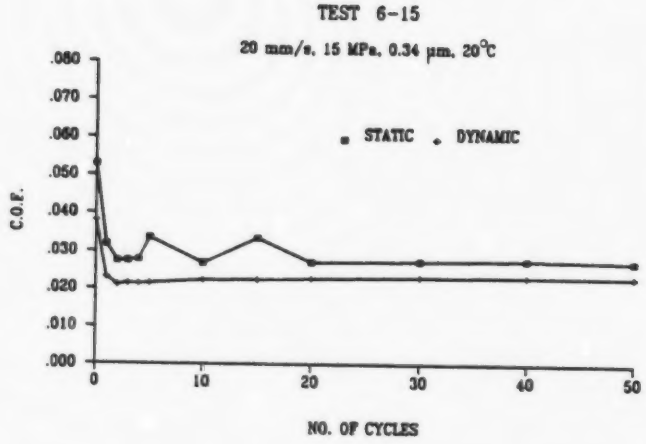

TEST 5-30
1 mm/s, 30 MPa, 0.34 μm, 20°C
▪ STATIC ▪ DYNAMIC
C.O.F.
.025
.020
.015
.010
.005
.000
50
100
150
200
250
300
350
400
NO. OF CYCLES

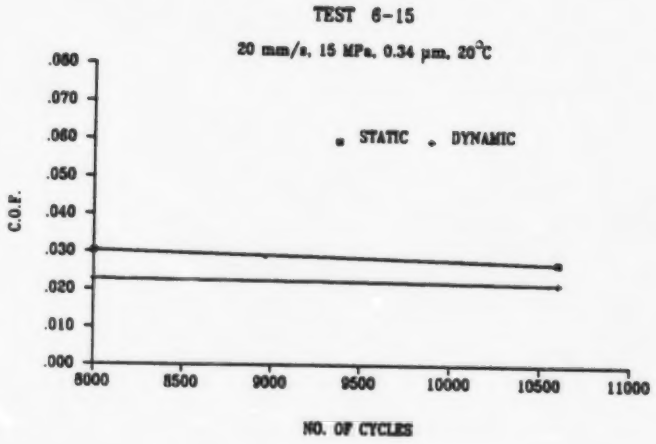

TEST 5-45
1 mm/s, 45 MPa, 0.34 μm, 20°C
STATIC
DYNAMIC
C.O.F.
.025
.020
.015
.010
.005
.000
0
10
20
30
40
50
NO. OF CYCLES

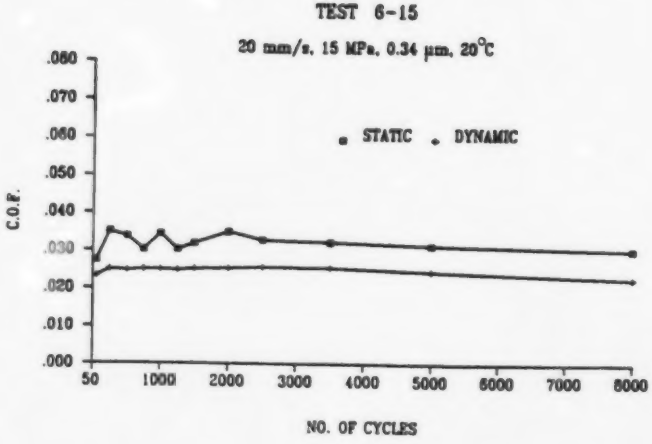

TEST 6-10
20 mm/s, 10 MPa, 0.34 μm, 20°C
STATIC
DYNAMIC
C.O.F.
.080
.070
.060
.050
.040
.030
.020
.010
.000
0
10
20
30
40
50
NO. OF CYCLES

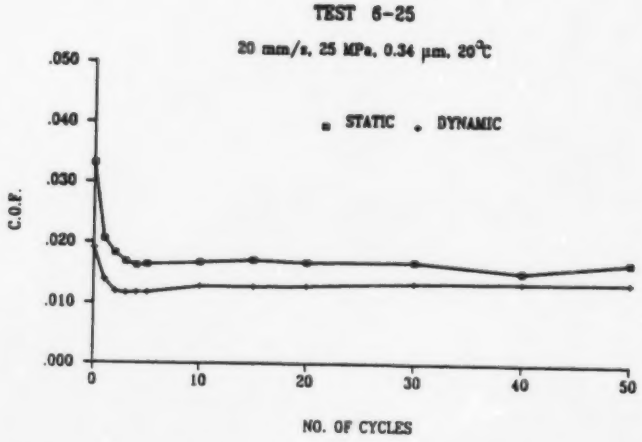

TEST 5-45
1 mm/s, 45 MPa, 0.34 μm, 20°C
STATIC
DYNAMIC
C.O.F.
.025
.020
.015
.010
.005
.000
50
100
150
200
250
300
350
400
NO. OF CYCLES

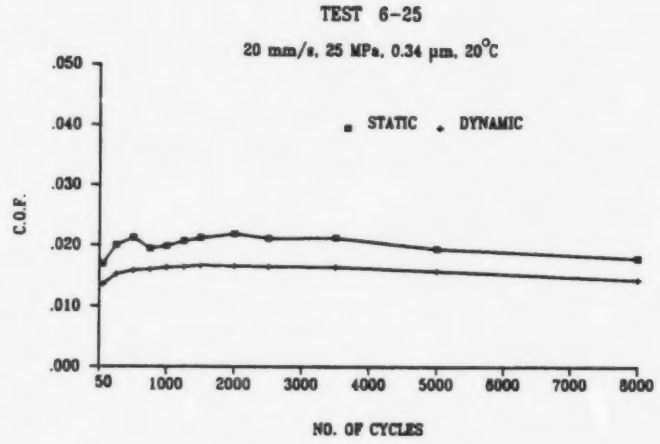

TEST 6-10
20 mm/s, 10 MPa, 0.34 μm, 20°C
STATIC
DYNAMIC
C.O.F.
.080
.070
.060
.050
.040
.030
.020
.010
.000
50
1000
2000
3000
4000
5000
6000
7000
8000
NO. OF CYCLES

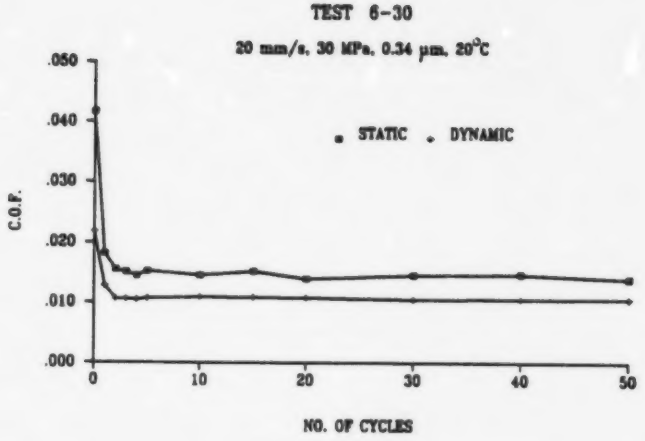

TEST 6-15
20 mm/s, 15 MPa, 0.34 μm, 20°C
■ STATIC ◆ DYNAMIC
C.O.F.
.080
.070
.060
.050
.040
.030
.020
.010
.000
0
10
20
30
40
50
NO. OF CYCLES

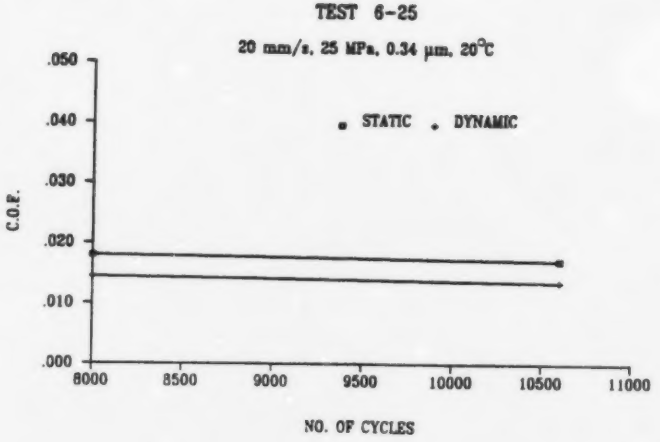

TEST 6-15
20 mm/s, 15 MPa, 0.34 μm, 20°C
■ STATIC ◆ DYNAMIC
C.O.F.
.080
.070
.060
.050
.040
.030
.020
.010
.000
8000
8500
9000
9500
10000
10500
11000
NO. OF CYCLES

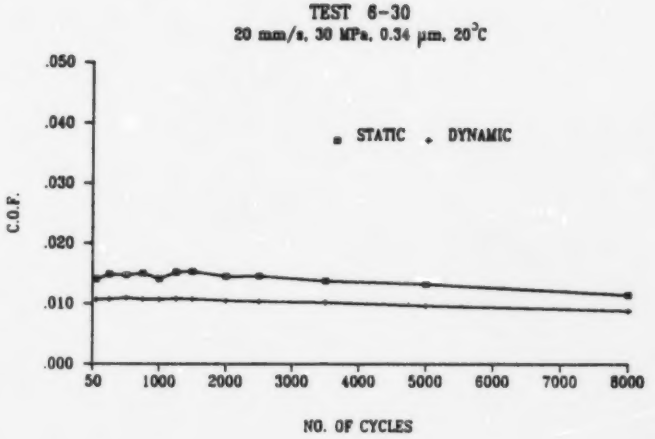

TEST 6-15
20 mm/s, 15 MPa, 0.34 μm, 20°C
■ STATIC ◆ DYNAMIC
C.O.F.
.080
.070
.060
.050
.040
.030
.020
.010
.000
50
1000
2000
3000
4000
5000
6000
7000
8000
NO. OF CYCLES

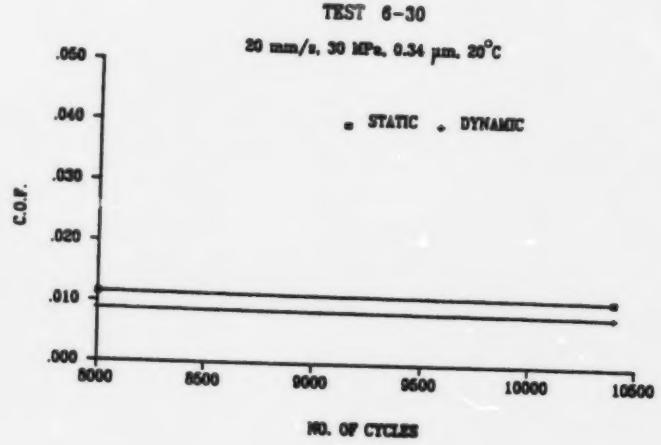

TEST 6-25
20 mm/s, 25 MPa, 0.34 μm, 20°C
■ STATIC ◆ DYNAMIC
C.O.F.
.050
.040
.030
.020
.010
.000
0
10
20
30
40
50
NO. OF CYCLES

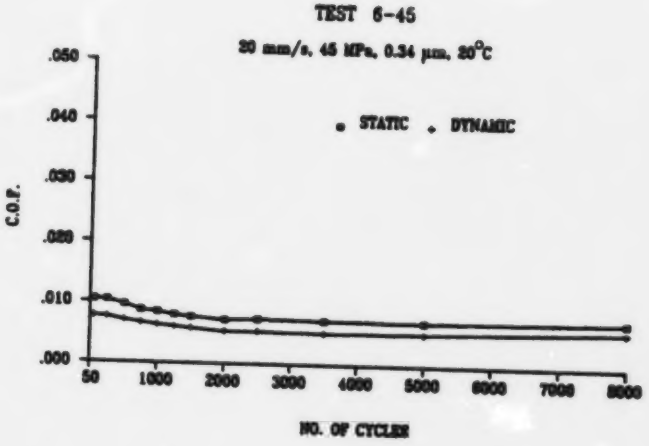

TEST 6-25
20 mm/s, 25 MPa, 0.34 μm, 20°C
STATIC
DYNAMIC
C.O.F.
.050
.040
.030
.020
.010
.000
50
1000
2000
3000
4000
5000
6000
7000
8000
NO. OF CYCLES

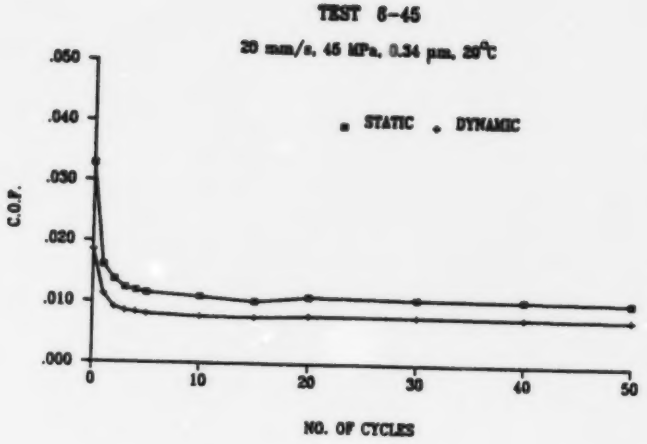

TEST 6-30
20 mm/s, 30 MPa, 0.34 μm, 20°C
STATIC
DYNAMIC
C.O.F.
.050
.040
.030
.020
.010
.000
0
10
20
30
40
50
NO. OF CYCLES

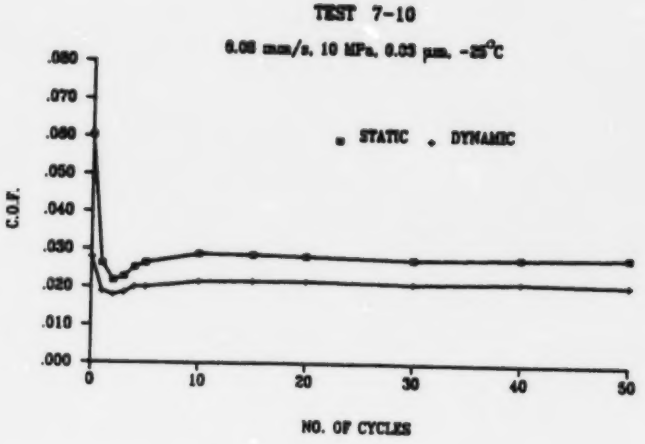

TEST 6-25
20 mm/s, 25 MPa, 0.34 μm, 20°C
STATIC
DYNAMIC
C.O.F.
.050
.040
.030
.020
.010
.000
8000
8500
9000
9500
10000
10500
11000
NO. OF CYCLES

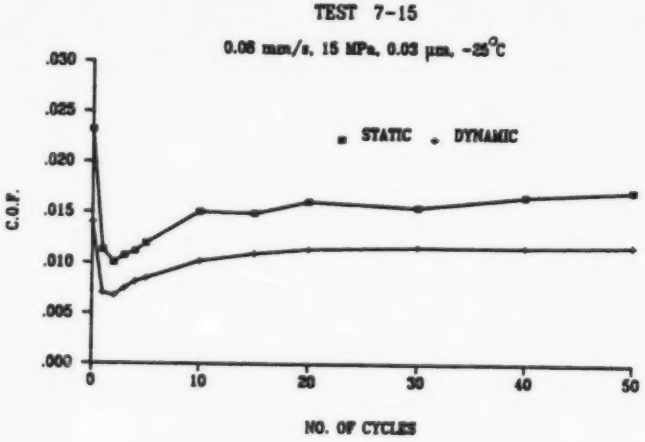

TEST 6-30
20 mm/s, 30 MPa, 0.34 μm, 20°C
STATIC
DYNAMIC
C.O.F.
.050
.040
.030
.020
.010
.000
50
1000
2000
3000
4000
5000
6000
7000
8000
NO. OF CYCLES

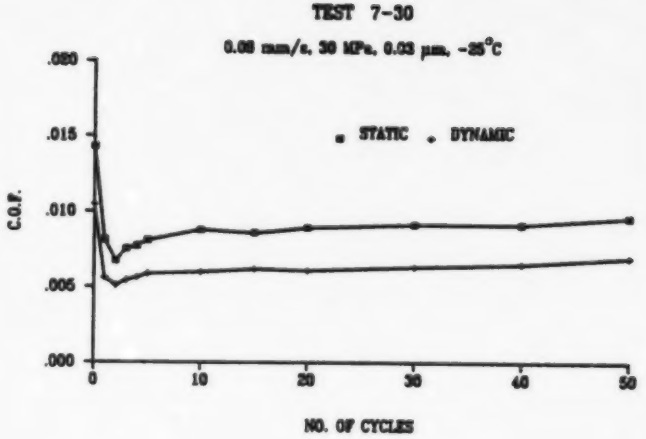

TEST 6-30
20 mm/s, 30 MPa, 0.34 μm, 20°C
▪ STATIC ◆ DYNAMIC
C.O.F.
.050
.040
.030
.020
.010
.000
8000
8500
9000
9500
10000
10500
NO. OF CYCLES

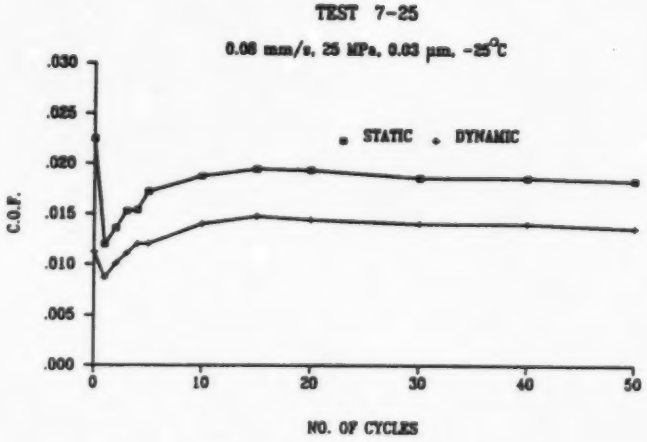

TEST 6-45
20 mm/s, 45 MPa, 0.34 μm, 20°C
▪ STATIC ◆ DYNAMIC
C.O.F.
.050
.040
.030
.020
.010
.000
50
1000
2000
3000
4000
5000
6000
7000
8000
NO. OF CYCLES

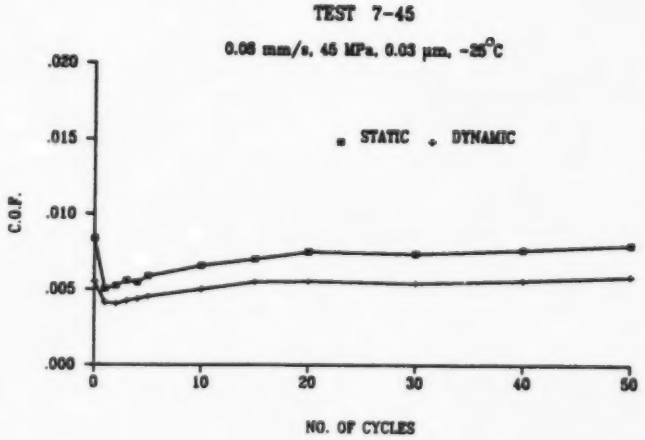

TEST 6-45
20 mm/s, 45 MPa, 0.34 μm, 20°C
▪ STATIC ◆ DYNAMIC
C.O.F.
.050
.040
.030
.020
.010
.000
0
10
20
30
40
50
NO. OF CYCLES

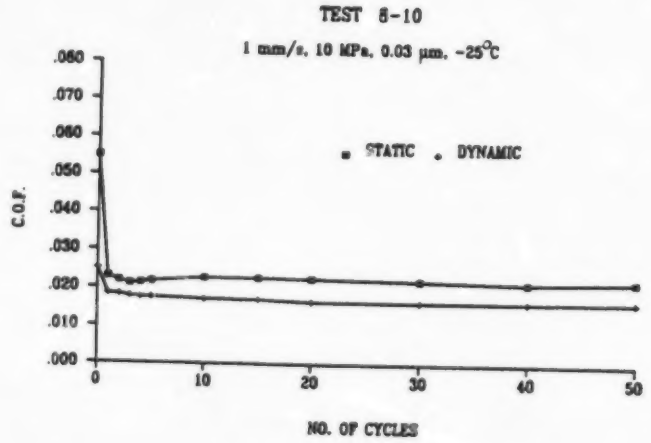

TEST 7-10
0.08 mm/s, 10 MPa, 0.03 μm, -25°C
▪ STATIC ◆ DYNAMIC
C.O.F.
.080
.070
.060
.050
.040
.030
.020
.010
.000
0
10
20
30
40
50
NO. OF CYCLES

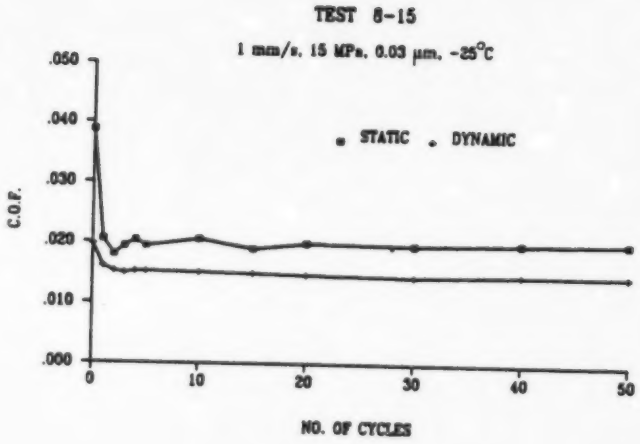

TEST 7-15
0.06 mm/s, 15 MPa, 0.03 μm, -25°C
■ STATIC ◆ DYNAMIC
C.O.F.
.030
.025
.020
.015
.010
.005
.000
0
10
20
30
40
50
NO. OF CYCLES

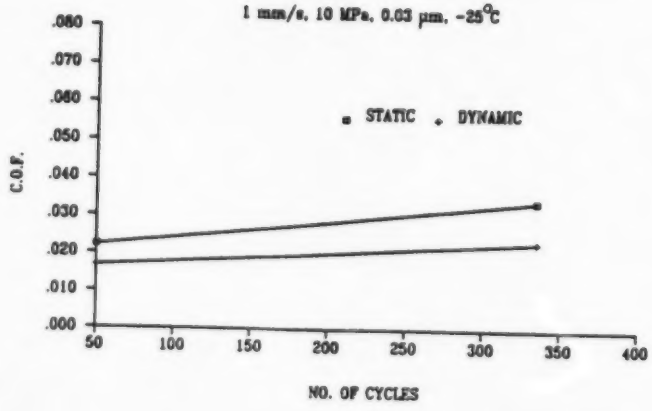

TEST 7-30
0.06 mm/s, 30 MPa, 0.03 μm, -25°C
■ STATIC ◆ DYNAMIC
C.O.F.
.020
.015
.010
.005
.000
0
10
20
30
40
50
NO. OF CYCLES

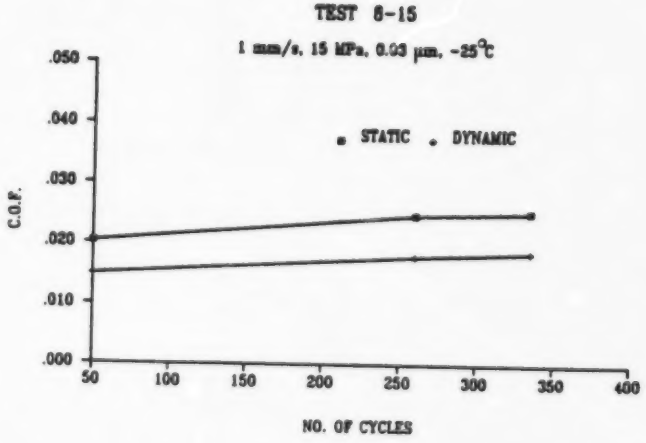

TEST 7-25
0.06 mm/s, 25 MPa, 0.03 μm, -25°C
■ STATIC ◆ DYNAMIC
C.O.F.
.030
.025
.020
.015
.010
.005
.000
0
10
20
30
40
50
NO. OF CYCLES

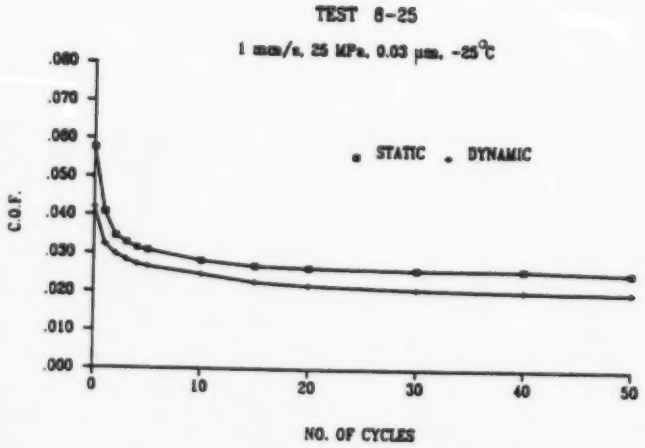

TEST 7-45
0.06 mm/s, 45 MPa, 0.03 μm, -25°C
■ STATIC ◆ DYNAMIC
C.O.F.
.020
.015
.010
.005
.000
0
10
20
30
40
50
NO. OF CYCLES

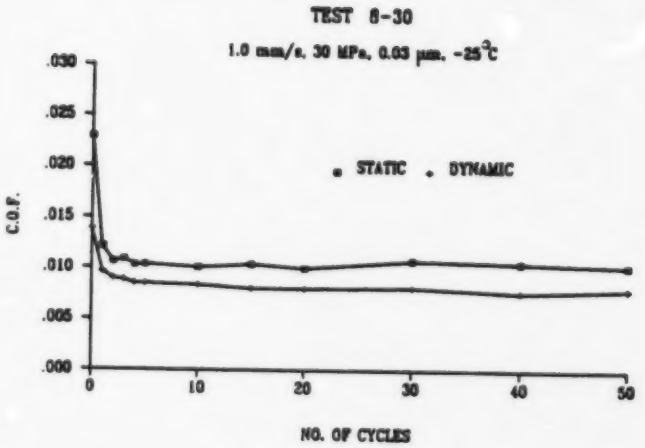

TEST 8-10
1 mm/s, 10 MPa, 0.03 μm, -25°C
STATIC
DYNAMIC
C.O.F.
.060
.070
.080
.050
.040
.030
.020
.010
.000
0
10
20
30
40
50
NO. OF CYCLES

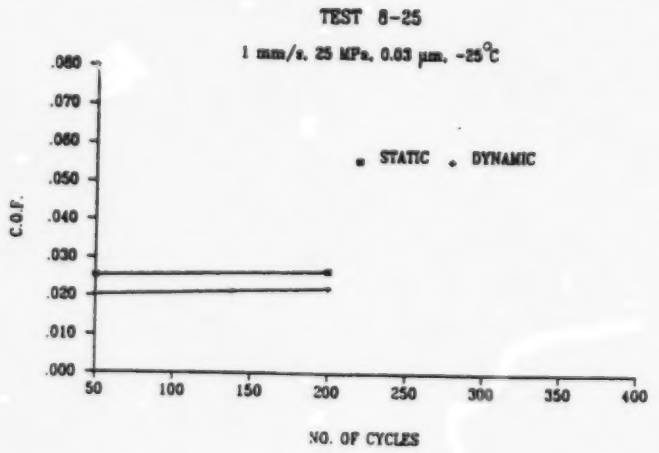

TEST 8-15
1 mm/s, 15 MPa, 0.03 μm, -25°C
STATIC
DYNAMIC
C.O.F.
.050
.040
.030
.020
.010
.000
0
10
20
30
40
50
NO. OF CYCLES

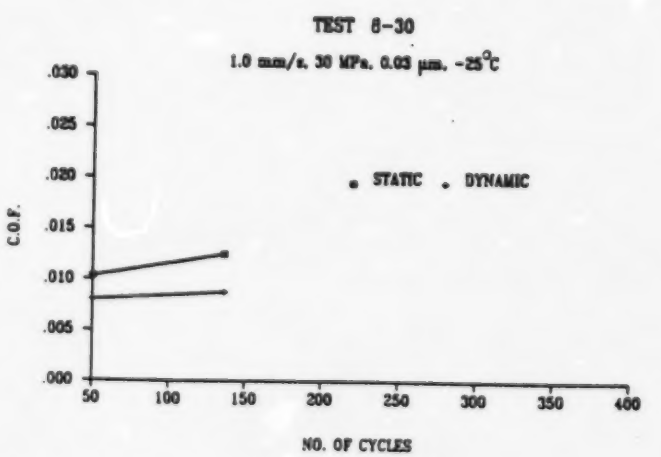

TEST 8-10
1 mm/s, 10 MPa, 0.03 μm, -25°C
STATIC
DYNAMIC
C.O.F.
.060
.070
.080
.050
.040
.030
.020
.010
.000
50
100
150
200
250
300
350
400
NO. OF CYCLES

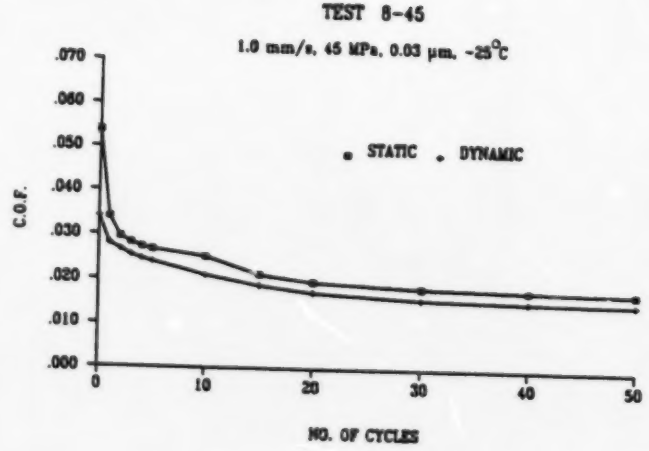

TEST 8-15
1 mm/s, 15 MPa, 0.03 μm, -25°C
STATIC
DYNAMIC
C.O.F.
.050
.040
.030
.020
.010
.000
50
100
150
200
250
300
350
400
NO. OF CYCLES

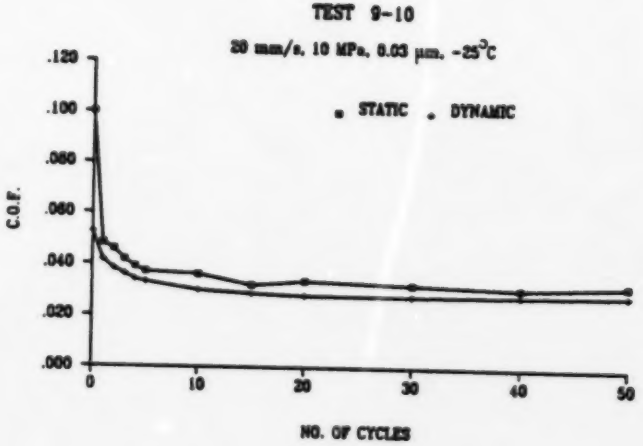

TEST 8-25
1 mm/s, 25 MPa, 0.03 μm, -25°C
• STATIC ▪ DYNAMIC
C.O.F.
.080
.070
.060
.050
.040
.030
.020
.010
.000
0
10
20
30
40
50
NO. OF CYCLES

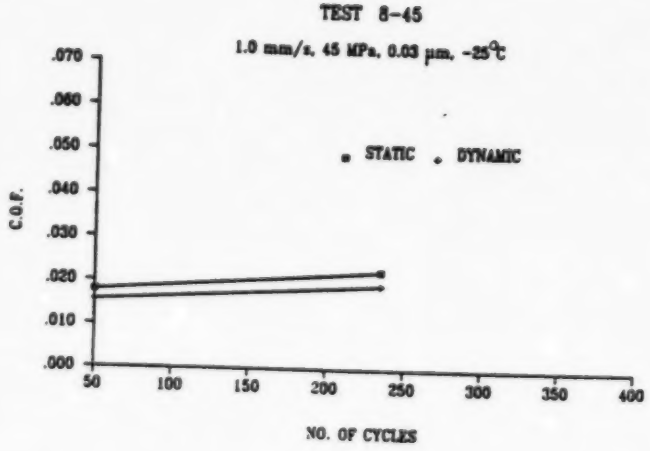

TEST 8-30
1.0 mm/s, 30 MPa, 0.03 μm, -25°C
• STATIC ▪ DYNAMIC
C.O.F.
.030
.025
.020
.015
.010
.005
.000
0
10
20
30
40
50
NO. OF CYCLES

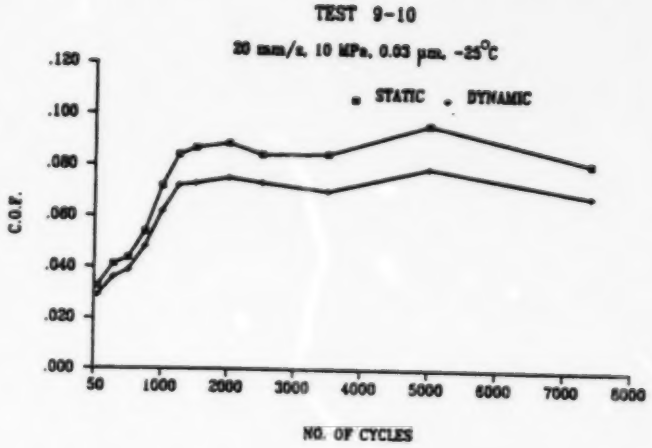

TEST 8-25
1 mm/s, 25 MPa, 0.03 μm, -25°C
• STATIC ▪ DYNAMIC
C.O.F.
.080
.070
.060
.050
.040
.030
.020
.010
.000
50
100
150
200
250
300
350
400
NO. OF CYCLES

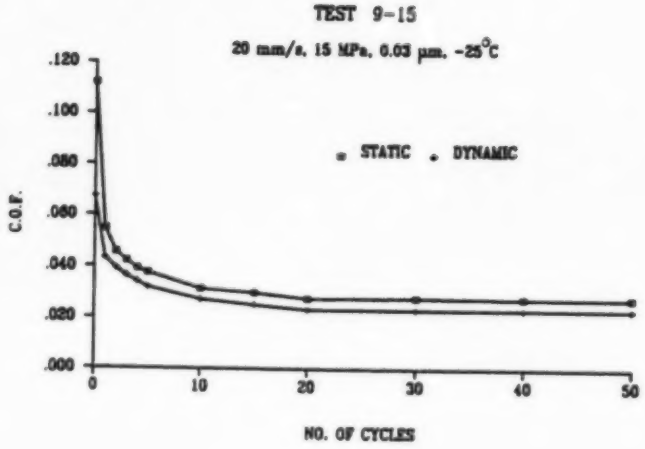

TEST 8-30
1.0 mm/s, 30 MPa, 0.03 μm, -25°C
• STATIC ▪ DYNAMIC
C.O.F.
.030
.025
.020
.015
.010
.005
.000
50
100
150
200
250
300
350
400
NO. OF CYCLES

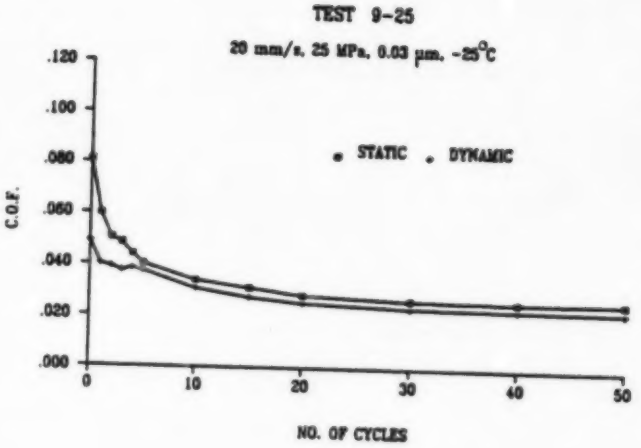

TEST 8-45
1.0 mm/s, 45 MPa, 0.03 μm, -25°C
■ STATIC ▲ DYNAMIC
C.O.F.
.070
.060
.050
.040
.030
.020
.010
.000
0
10
20
30
40
50
NO. OF CYCLES

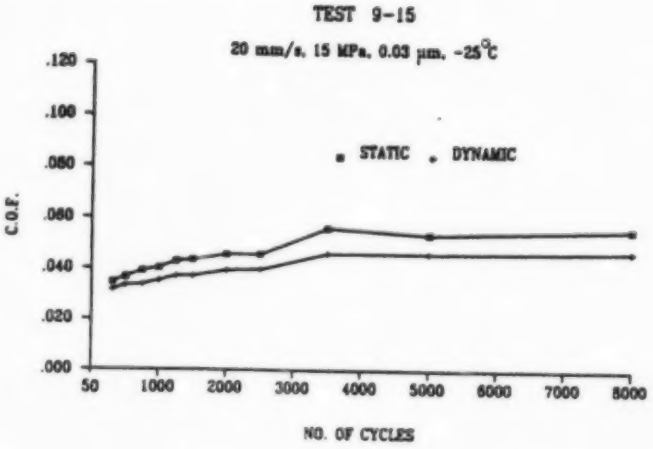

TEST 9-10
20 mm/s, 10 MPa, 0.03 μm, -25°C
■ STATIC ▲ DYNAMIC
C.O.F.
.120
.100
.080
.060
.040
.020
.000
0
10
20
30
40
50
NO. OF CYCLES

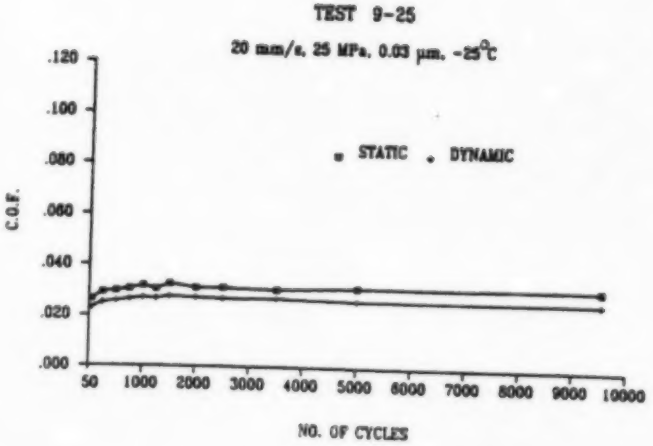

TEST 8-45
1.0 mm/s, 45 MPa, 0.03 μm, -25°C
■ STATIC ▲ DYNAMIC
C.O.F.
.070
.060
.050
.040
.030
.020
.010
.000
50
100
150
200
250
300
350
400
NO. OF CYCLES

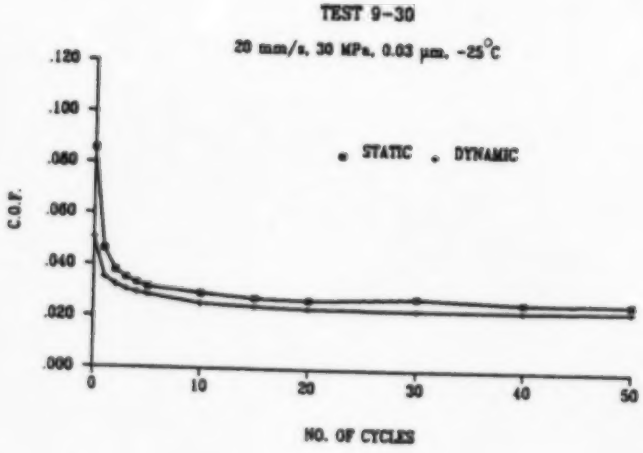

TEST 9-10
20 mm/s, 10 MPa, 0.03 μm, -25°C
■ STATIC ▲ DYNAMIC
C.O.F.
.120
.100
.080
.060
.040
.020
.000
50
1000
2000
3000
4000
5000
6000
7000
8000
NO. OF CYCLES

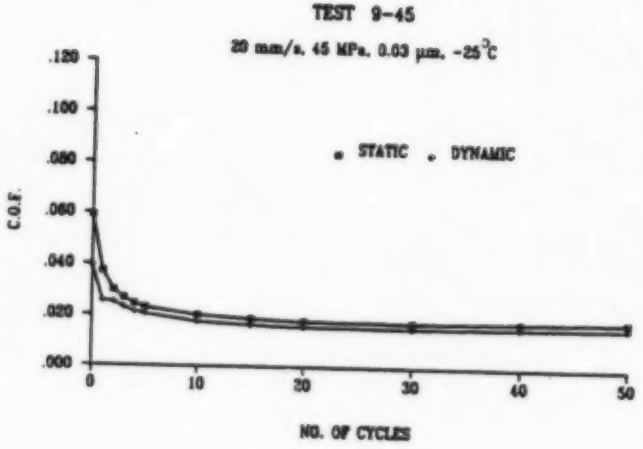

TEST 9-15
20 mm/s, 15 MPa, 0.03 μm, -25°C
▪ STATIC ▪ DYNAMIC
C.O.F.
.120
.100
.080
.060
.040
.020
.000
0
10
20
30
40
50
NO. OF CYCLES

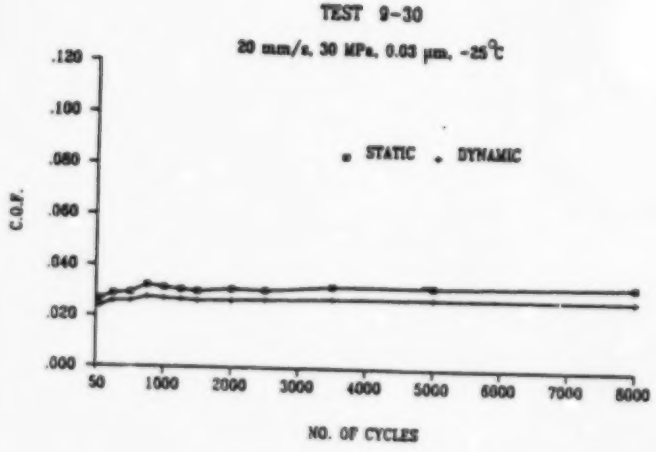

TEST 9-25
20 mm/s, 25 MPa, 0.03 μm, -25°C
▪ STATIC ▪ DYNAMIC
C.O.F.
.120
.100
.080
.060
.040
.020
.000
0
10
20
30
40
50
NO. OF CYCLES

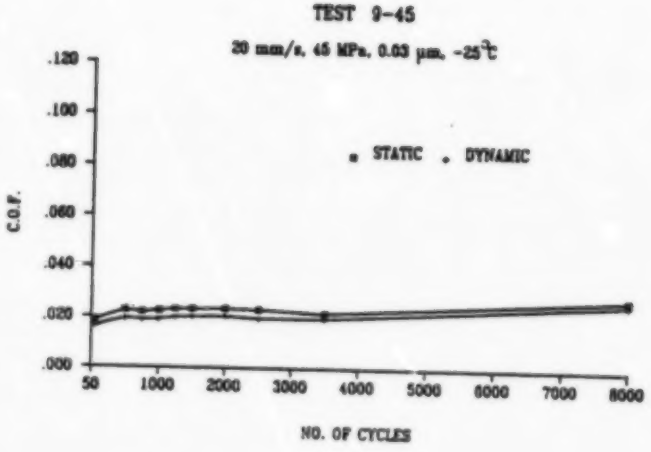

TEST 9-15
20 mm/s, 15 MPa, 0.03 μm, -25°C
▪ STATIC ▪ DYNAMIC
C.O.F.
.120
.100
.080
.060
.040
.020
.000
50
1000
2000
3000
4000
5000
6000
7000
8000
NO. OF CYCLES

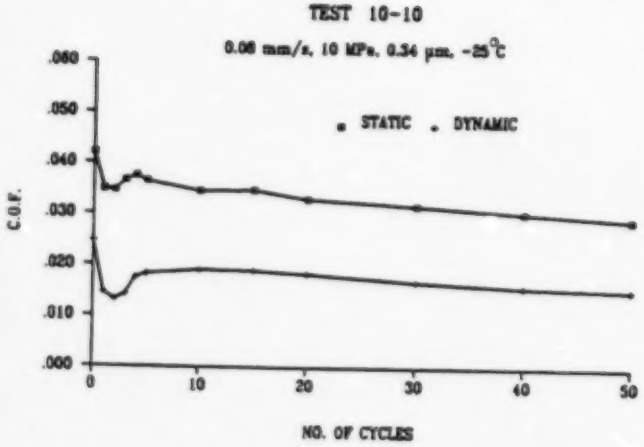

TEST 9-25
20 mm/s, 25 MPa, 0.03 μm, -25°C
▪ STATIC ▪ DYNAMIC
C.O.F.
.120
.100
.080
.060
.040
.020
.000
50
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
NO. OF CYCLES

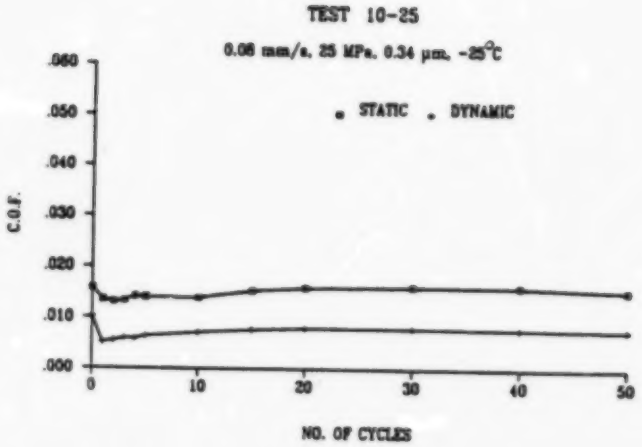

TEST 9-30
20 mm/s, 30 MPa, 0.03 μm, -25°C
• STATIC ▪ DYNAMIC
C.O.F.
.120
.100
.080
.060
.040
.020
.000
0
10
20
30
40
50
NO. OF CYCLES

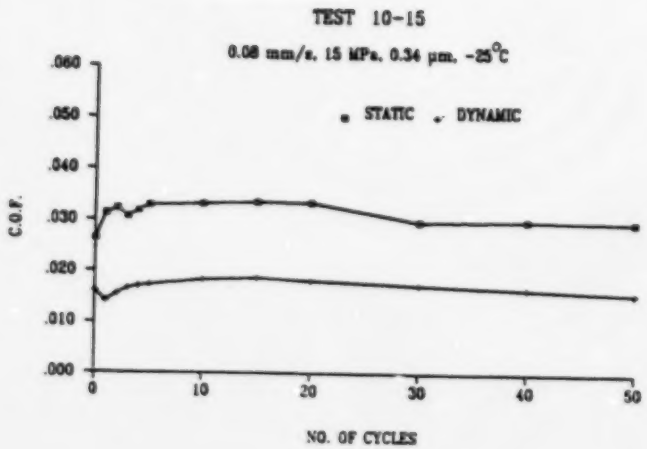

TEST 9-45
20 mm/s, 45 MPa, 0.03 μm, -25°C
• STATIC ▪ DYNAMIC
C.O.F.
.120
.100
.080
.060
.040
.020
.000
0
10
20
30
40
50
NO. OF CYCLES

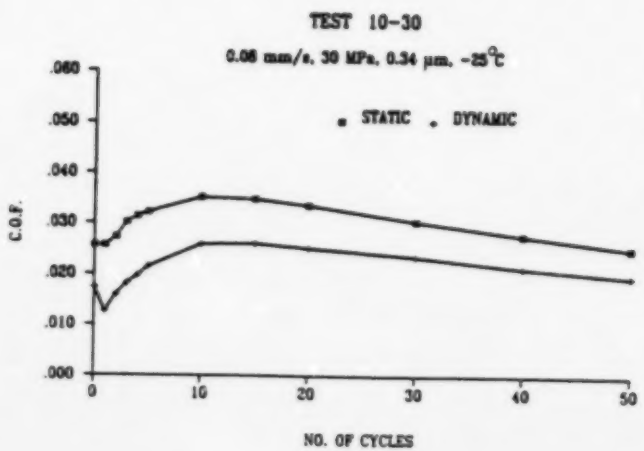

TEST 9-30
20 mm/s, 30 MPa, 0.03 μm, -25°C
• STATIC ▪ DYNAMIC
C.O.F.
.120
.100
.080
.060
.040
.020
.000
50
1000
2000
3000
4000
5000
6000
7000
8000
NO. OF CYCLES

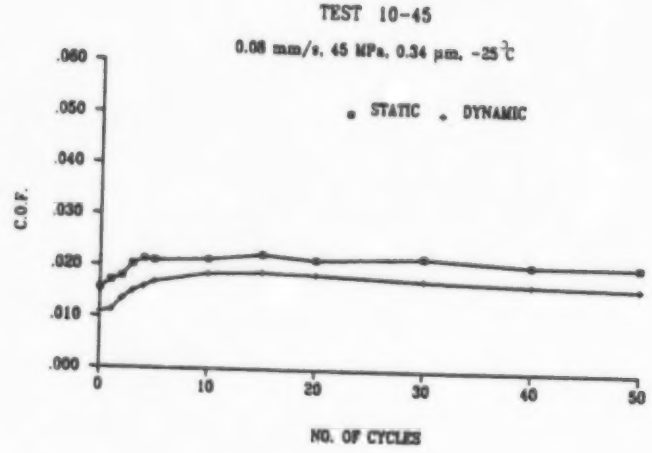

TEST 9-45
20 mm/s, 45 MPa, 0.03 μm, -25°C
• STATIC ▪ DYNAMIC
C.O.F.
.120
.100
.080
.060
.040
.020
.000
50
1000
2000
3000
4000
5000
6000
7000
8000
NO. OF CYCLES

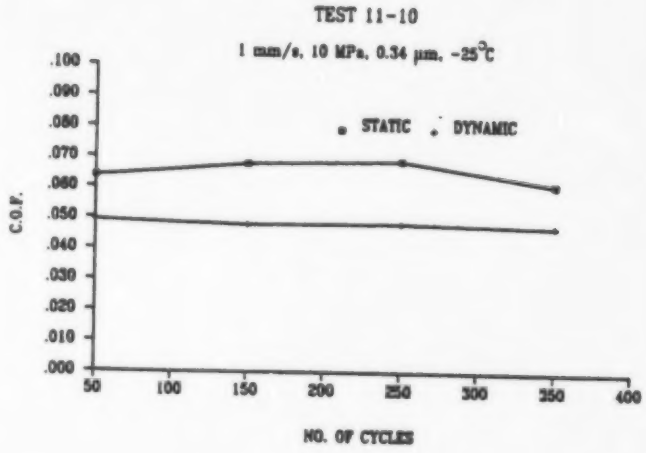

TEST 10-10
0.06 mm/s, 10 MPa, 0.34 μm, -25°C
• STATIC ◦ DYNAMIC
C.O.F.
.060
.050
.040
.030
.020
.010
.000
0
10
20
30
40
50
NO. OF CYCLES

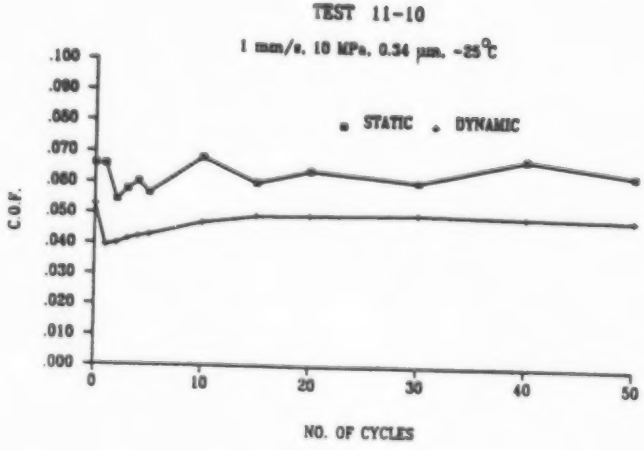

TEST 10-25
0.06 mm/s, 25 MPa, 0.34 μm, -25°C
• STATIC ◦ DYNAMIC
C.O.F.
.060
.050
.040
.030
.020
.010
.000
0
10
20
30
40
50
NO. OF CYCLES

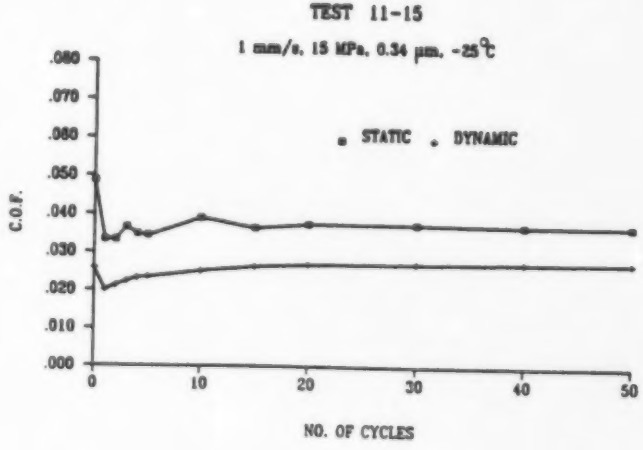

TEST 10-15
0.06 mm/s, 15 MPa, 0.34 μm, -25°C
• STATIC ◦ DYNAMIC
C.O.F.
.060
.050
.040
.030
.020
.010
.000
0
10
20
30
40
50
NO. OF CYCLES

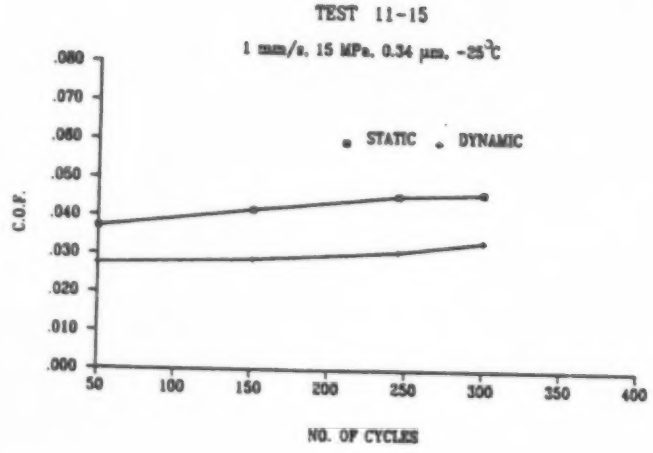

TEST 10-30
0.06 mm/s, 30 MPa, 0.34 μm, -25°C
• STATIC ◦ DYNAMIC
C.O.F.
.060
.050
.040
.030
.020
.010
.000
0
10
20
30
40
50
NO. OF CYCLES

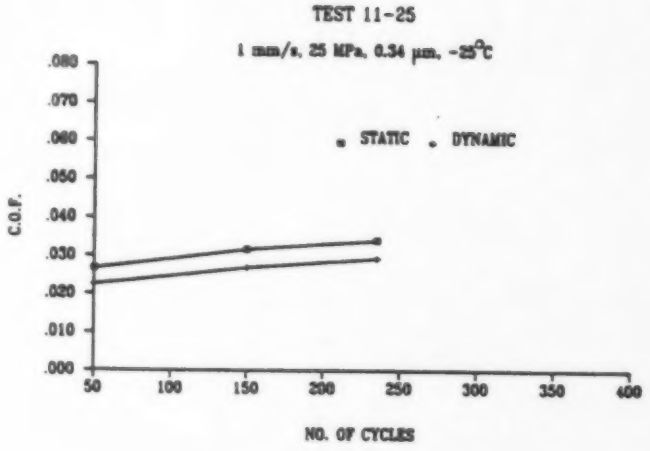

TEST 10-45
0.08 mm/s, 45 MPa, 0.34 μm, -25℃
• STATIC ▲ DYNAMIC
C.O.F.
.060
.050
.040
.030
.020
.010
.000
0
10
20
30
40
50
NO. OF CYCLES

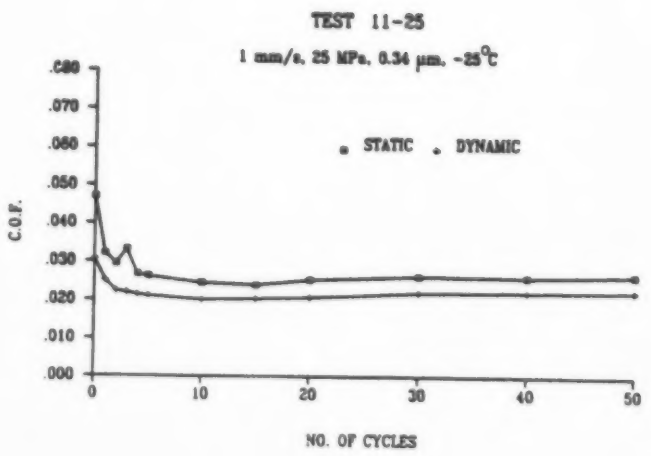

TEST 11-10
1 mm/s, 10 MPa, 0.34 μm, -25℃
• STATIC ▲ DYNAMIC
C.O.F.
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.000
50
100
150
200
250
300
350
400
NO. OF CYCLES

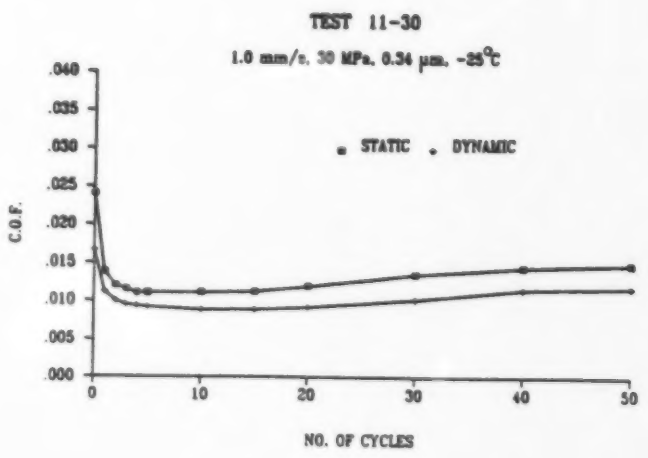

TEST 11-10
1 mm/s, 10 MPa, 0.34 μm, -25℃
• STATIC ▲ DYNAMIC
C.O.F.
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.000
0
10
20
30
40
50
NO. OF CYCLES

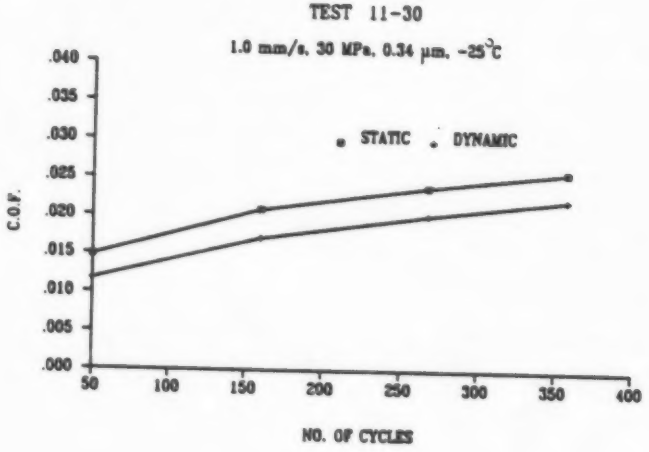

TEST 11-15
1 mm/s, 15 MPa, 0.34 μm, -25℃
• STATIC ▲ DYNAMIC
C.O.F.
.080
.070
.060
.050
.040
.030
.020
.010
.000
0
10
20
30
40
50
NO. OF CYCLES

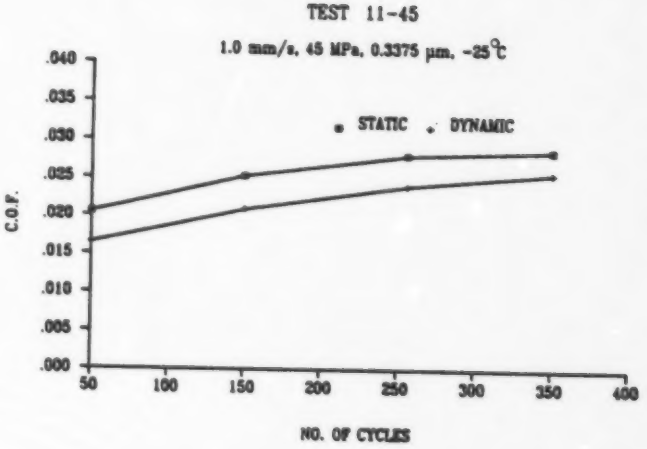

TEST 11-15
1 mm/s, 15 MPa, 0.34 μm, -25°C
STATIC
DYNAMIC
C.O.F.
.080
.070
.060
.050
.040
.030
.020
.010
.000
50
100
150
200
250
300
350
400
NO. OF CYCLES

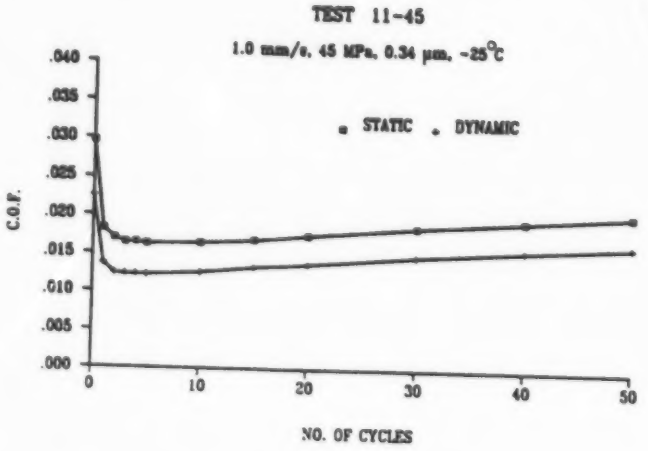

TEST 11-25
1 mm/s, 25 MPa, 0.34 μm, -25°C
STATIC
DYNAMIC
C.O.F.
.080
.070
.060
.050
.040
.030
.020
.010
.000
50
100
150
200
250
300
350
400
NO. OF CYCLES

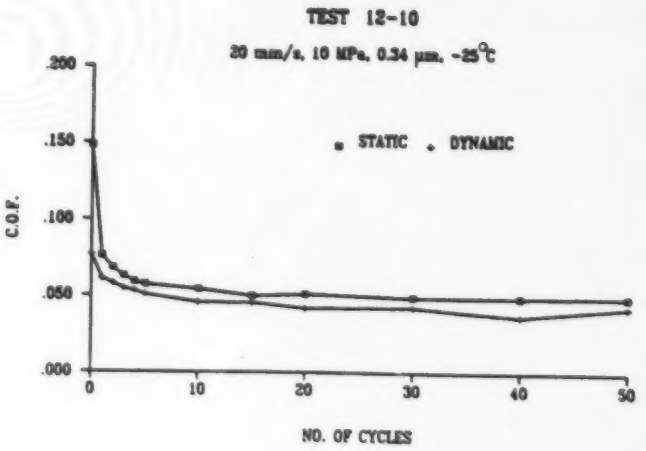

TEST 11-25
1 mm/s, 25 MPa, 0.34 μm, -25°C
STATIC
DYNAMIC
C.O.F.
.080
.070
.060
.050
.040
.030
.020
.010
.000
0
10
20
30
40
50
NO. OF CYCLES

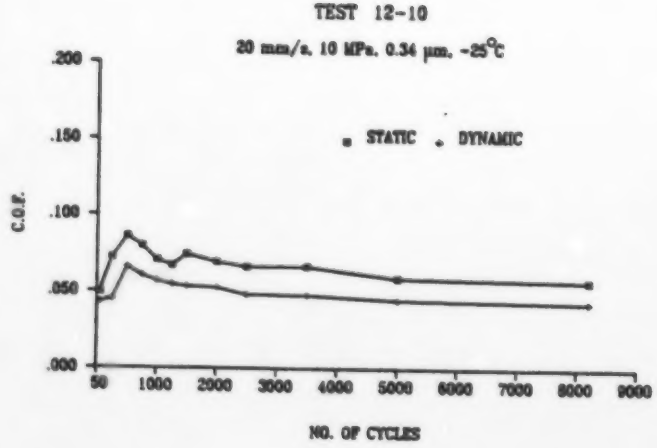

TEST 11-30
1.0 mm/s, 30 MPa, 0.34 μm, -25°C
STATIC
DYNAMIC
C.O.F.
.040
.035
.030
.025
.020
.015
.010
.005
.000
0
10
20
30
40
50
NO. OF CYCLES

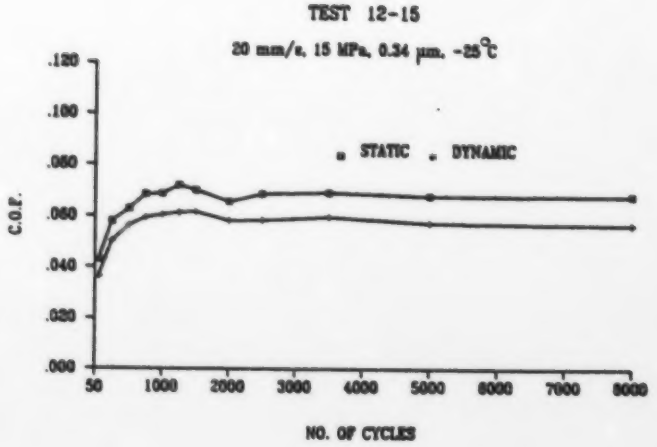

TEST 11-30
1.0 mm/s, 30 MPa, 0.34 μm, -25°C
▪ STATIC ▪ DYNAMIC
C.O.F.
.040
.035
.030
.025
.020
.015
.010
.005
.000
50
100
150
200
250
300
350
400
NO. OF CYCLES

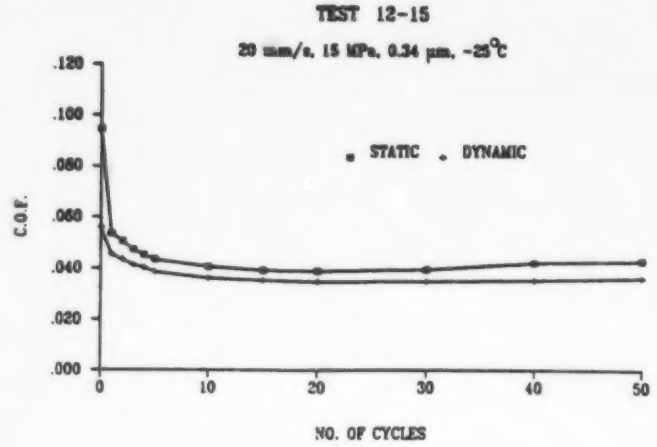

TEST 11-45
1.0 mm/s, 45 MPa, 0.3375 μm, -25°C
▪ STATIC ▪ DYNAMIC
C.O.F.
.040
.035
.030
.025
.020
.015
.010
.005
.000
50
100
150
200
250
300
350
400
NO. OF CYCLES

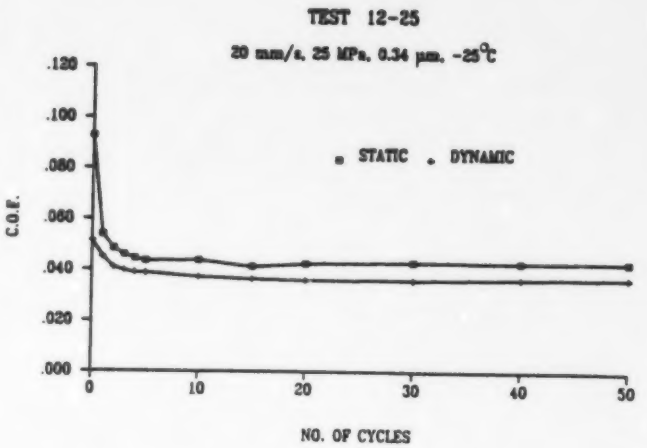

TEST 11-45
1.0 mm/s, 45 MPa, 0.34 μm, -25°C
▪ STATIC ▪ DYNAMIC
C.O.F.
.040
.035
.030
.025
.020
.015
.010
.005
.000
0
10
20
30
40
50
NO. OF CYCLES


TEST 12-10
20 mm/s, 10 MPa, 0.34 μm, -25°C
▪ STATIC ▪ DYNAMIC
C.O.F.
.200
.150
.100
.050
.000
0
10
20
30
40
50
NO. OF CYCLES


TEST 12-10
20 mm/s, 10 MPa, 0.34 μm, -25°C
■ STATIC ▲ DYNAMIC
C.O.F.
.200
.150
.100
.050
.000
50 1000 2000 3000 4000 5000 6000 7000 8000 9000
NO. OF CYCLES

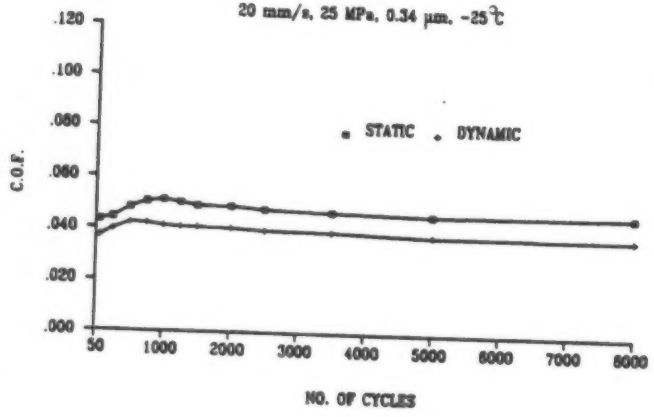

TEST 12-15
20 mm/s, 15 MPa, 0.34 μm, -25°C
■ STATIC ▲ DYNAMIC
C.O.F.
.120
.100
.080
.060
.040
.020
.000
50 1000 2000 3000 4000 5000 6000 7000 8000
NO. OF CYCLES


TEST 12-15
20 mm/s, 15 MPa, 0.34 μm, -25°C
■ STATIC ▲ DYNAMIC
C.O.F.
.120
.100
.080
.060
.040
.020
.000
0 10 20 30 40 50
NO. OF CYCLES


TEST 12-25
20 mm/s, 25 MPa, 0.34 μm, -25°C
■ STATIC ▲ DYNAMIC
C.O.F.
.120
.100
.080
.060
.040
.020
.000
0 10 20 30 40 50
NO. OF CYCLES

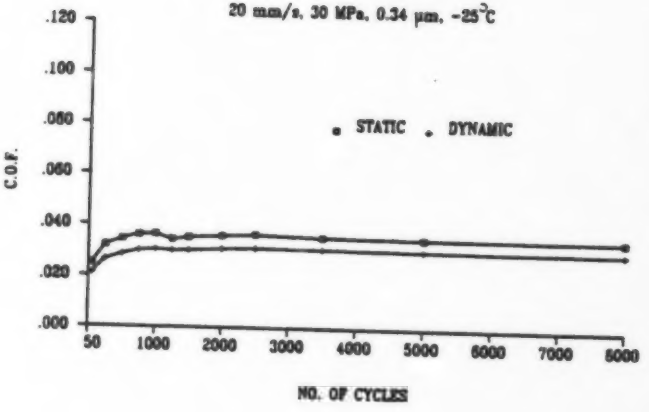
TEST 12-25

20 mm/s, 25 MPa, 0.34 μm, -25°C



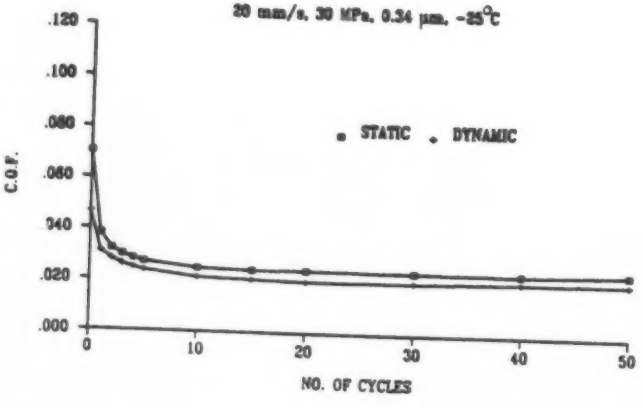
TEST 12-30

20 mm/s, 30 MPa, 0.34 μm, -25°C



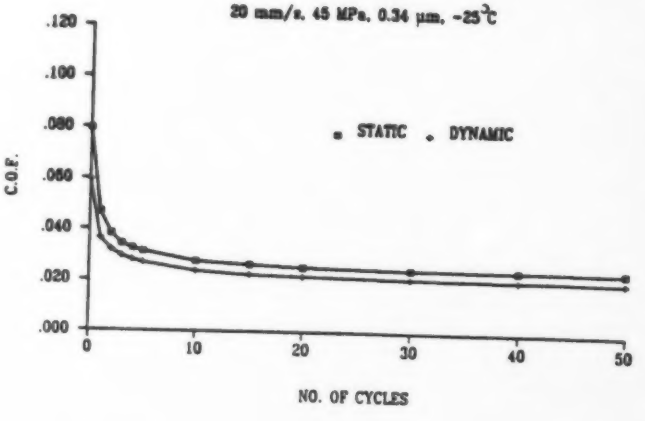
TEST 12-30

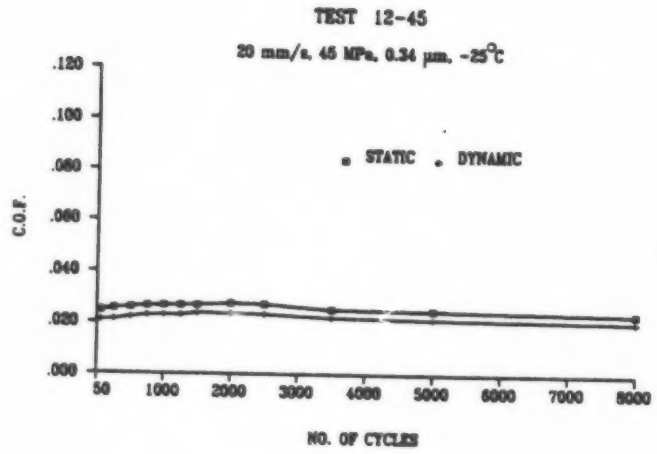
20 mm/s, 30 MPa, 0.34 μm, -25°C



TEST 12-45

20 mm/s, 45 MPa, 0.34 μm, -25°C




TEST 12-45
20 mm/s, 45 MPa, 0.34 μm, -25°C
▪ STATIC ▪ DYNAMIC
C.O.F.
.120
.100
.080
.060
.040
.020
.000
50
1000
2000
3000
4000
5000
6000
7000
8000
NO. OF CYCLES